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A PHYSIOLOGICAL STRAIN INDEX (PSI) TO EVALUATE HEAT STRESS

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13. ABSTRACT *(Maximum 200 words)*
Although there are many heat strain indices, we found that they were valid only under certain and specific conditions. The present study suggests a simple valid physiological strain index (PSI) to evaluate heat stress either on-line or when data analysis is applied. This index should be easier to interpret and use than other indices available, and includes the ability to depict rest and recovery periods. PSI is capable of overcoming the limits of previous indices, while providing the potential to be widely accepted and used universally. However, further investigation is required to possibly adjust this index for different age groups. The PSI successfully evaluated the heat stress in subjects who exercised in a warm environment at different exercise intensities combined with different levels of hypohydration. This index overcame the individual limits of the physiological parameters (Tre, Tes and HR) in assessing heat stress for this study, and continues to provide the potential to be accepted universally. The PSI also successfully evaluated heat stress and gender when exercising at different intensities in different climates. We have also extended the applicability of PSI in the present study to consider sweat rate and relative exercise intensity as a function of climate. Therefore, PSI applicability was further extended for exercised-heat stress and gender at different combinations of exercise intensity and climate, and continues to show potential to be widely accepted.

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LIST OF ABBREVIATIONS

A_D – body surface area

AUC_{Tre} – area under the T_{re} curve

AUC_{HR} – area under the HR curve

BMI – body mass index

BWL – body weight loss

CHSI – cumulative heat strain index

ET – effective temperature

E_{req} – total evaporative required

E_{max} – evaporative capacity of the environment

HR – heart rate

HR_0 – initial heart rate

H_{r+c} – heat transfer between the body and the environment by radiation and convection

HSI – heat strain index

ISI – integral stress index

M – metabolic heat production

$\dot{m}_{sw}$ – sweat rate

PSI – physiological strain index

P4SR – predicted 4 hour sweat rate

RH – relative humidity

RPE – rating of perceived exertion

Δt – time interval for measuring data

TO – operative temperature

T_{es} – esophageal temperature

T_{re} – rectal temperature

T_{re0} – initial rectal temperature

T_{sk} – skin temperature

$\dot{V}O_2$ – oxygen consumption

$\dot{V}O_{2max}$ – maximal oxygen consumption

$\%\dot{V}O_{2max}$ – relative oxygen consumption $[100(\dot{V}O_2/\dot{V}O_{2max})]$

wt – body weight

EXECUTIVE SUMMARY

This report summarizes the development of a new physiological strain index (PSI) to assess heat stress. Three independent studies, containing five different databases were analyzed in order to evaluate PSI for different climate conditions, hydration levels, types of clothing, exercise intensities, and gender.

The purpose of the first study was to develop a simple index to be used in hot environments. The index was expected to be sensitive enough to differentiate between similar exposures that differ in one variable (e.g., clothing, metabolic rate, climate). The new suggested PSI, based on rectal temperature (T_{re}) and heart rate (HR), was capable of indicating heat strain on-line and analyzing existing databases. It was assumed that the maximal T_{re} and HR rise during exposure to exercise-heat stress from normothermia to hyperthermia was 3°C (36.5°C to 39.5°C) and 120 bpm (60 bpm to 180 bpm), respectively. T_{re} and HR were assigned the same weight functions as follows:

$$PSI=5(T_{ret}-T_{re0})\cdot(39.5-T_{re0})^{-1}+5(HR_t-HR_0)\cdot(180-HR_0)^{-1}$$

where T_{ret} and HR_t are simultaneous measurements taken at any time during the exposure.

PSI was applied to data obtained from 100 men performing exercise in the heat (40°C, 40% RH; 1.34 $m\cdot sec^{-1}$ at a 2% grade) for 120 min. A separate database representing 7 men wearing protective clothing and exercising in hot/dry and hot/wet environmental conditions was applied to test the validity of PSI, and differentiated significantly ($P<0.05$) between the two climates. For these two databases, the index rates the physiological strain on a universal scale of 0-10.

The purpose of the second study was to evaluate PSI for different combinations of hydration level and exercise intensity. The index was applied to two databases. The first database was obtained from eight endurance-trained men dehydrated to four different levels (1.1%, 2.3%, 3.4%, and 4.2% of body weight) during 120 min of cycling at a power output of 62%-67% $\dot{V}O_{2max}$ in the heat (33°C, 50% RH). The second database was obtained from nine men performing exercise in the heat (30°C, 50% RH) for 50 min. These subjects completed a matrix of nine trials exercising on a treadmill at three exercise intensities (25%, 45%, and 65% $\dot{V}O_{2max}$) and three hydration levels (euhydration and hypohydration at 3 and 5% of body weight). T_{re}, HR, esophageal temperature (T_{es}) and local sweating rate were measured. PSI (obtained from either T_{re} or T_{es}) significantly differentiated ($P<0.05$) between all exposures in both databases categorized by exercise intensity and hydration level, and assessed the strain on a scale ranging from 0-10. Therefore, PSI applicability was extended for heat strain associated with hypohydration.

The purpose of the third study was to evaluate PSI for gender differences under various combinations of exercise intensity and climate. Two groups of eight men each were formulated according to $\dot{V}O_{2max}$. The first group of men (M) was matched to a group of nine women (W) with similar (P>0.001) $\dot{V}O_{2max}$ (46.1±2.0 and 43.6±2.9 ml·kg^{-1}·min^{-1}, respectively). The second group of men (MF) was significantly (P<0.001) more fit than M or W with $\dot{V}O_{2max}$ of 59.1±1.8 ml·kg^{-1}·min^{-1}. Subjects completed a matrix of nine experimental combinations consisting of three different exercise intensities for 60 min: low, moderate, and high (300W, 500W, and 650W, respectively), each at three climates: comfortable, hot/wet, and hot/dry (20°C 50%RH, 35°C 70%RH, and 40°C 35% RH, respectively). No significant differences (P>0.05) were found between matched genders (M and W) at the same exposure for sweat rate, relative oxygen consumption (%$\dot{V}O_{2max}$), and PSI. However, MF had significantly (P<0.05) lower strain than M and W as reflected by %$\dot{V}O_{2max}$ and PSI. In summary, PSI applicability was extended for exercised-heat stress and gender. This index has the potential to be widely accepted and to serve universally.

INTRODUCTION

The physiological criterion of heat strain was probably best defined in 1905 by Haldane as the inability to maintain body core temperature at the level prescribed by the thermoregulatory center (19). This criterion has been adopted by many investigators, especially those who were concerned with safety limits for occupational exposure to heat.

During the last 100 years, attempts and efforts were made to combine environmental parameters and physiological variables by developing a unified heat stress index. Although over 20 heat strain indices already exist, not one is accepted as a universal physiological strain index. The main reason is probably related to the number and complexity of the interactions among the determining factors.

The existing indices can be divided into two main categories: effective temperature (ET) scales that are based on meteorological parameters only (e.g., ambient temperature, wet-bulb temperature, black-globe temperature), and rational heat scales, which include a combination of environmental and physiological parameters (e.g., radiative and convective heat transfer, evaporative capacity of the environment, and metabolic heat production). In 1923, Houghton and Yaglou (27) developed the ET index from which at least five additional indices were derived, among them the Wet Bulb Globe Temperature (WBGT) (67). A modified version of ET was suggested in 1986 by Gagge et al. (13), which was based on more sophisticated heat exchange models (25). The ET indices are widely applied to both assess and predict heat strain. However, they lack the capability to adjust for different levels of metabolic rate and different clothing, e.g. impermeable clothing (17, 29, 51).

In 1937, Winslow et al. (65) developed the operative temperature index (TO) which considered of the metabolic heat production (M), heat transfer between the body and the environment (H_{r+c}), and the evaporative capacity of the environment to dissipate heat (E_{max}). Based on the TO index, more than eight additional indices have been developed (3). The best known of these is the Heat Strain Index (HSI) suggested by Belding and Hatch (4). This index, which related $M+H_{r+c}$ (total evaporation required-E_{req}) to E_{max}, is widely accepted because it combines environmental variables and body activity. However, according to Belding (3), there were situations in which heat strain was seriously underpredicted or overpredicted by this index, and corrections were developed for improving the prediction of the index for various exposures (4, 14, 22, 25, 31, 34).

Heat strain indices based on physiological parameters were also suggested. McArdle et al. (33) developed the predicted 4-hour sweat rate index (P4SR), which uses sweat rate as an indicator of heat strain and predicts sweat rate for 4 hours for different combinations of M and climatic conditions. However, it was shown that sweat production by itself does not comprehensively represent heat strain (4, 22). The P4SR

was found relevant only for fit-acclimatized men (31). Robinson et al. (52) suggested an index of physiological effects which relied on rectal temperature (T_{re}), heart rate (HR), skin temperature (T_{sk}), and sweat rate ($\dot{m}_{sw}$). The index, based on an equal weight for the four parameters with no relation to the metabolic state, was developed on the basis of data collected involving acclimatized subjects, but was not validated for other conditions. In 1960, Hall and Plote (20) suggested an index of physiological strain based on body heat storage and also used T_{re}, HR and $\dot{m}_{sw}$. The complexity of calculating this index and the inability to rate the strain on-line were the main reasons for it not being universally accepted.

In 1989, Hubac et al. (28) suggested a different method to evaluate heat strain. Their index was based on integration of HSI and data obtained from HR and $\dot{m}_{sw}$ measurements. However, this index, which was developed for an 8-hour work shift without rest, was limited and involved complex calculations.

In 1996, Frank et al. (11) introduced a cumulative heat strain index (CHSI) based on T_{re} and heart beats. The index was developed in order to facilitate an improved criterion for evaluating heat-intolerant subjects, and was based on data from heat-intolerance tests. Recently, Gonzalez et al. (16) suggested in a study which was conducted in three different laboratories and included a large number of subjects, that a protective clothing heat strain model should be based only on T_{re}. This proposed index, however, could be applied only to certain exposure conditions (e.g., protective clothing systems). Although there are many heat strain indices, it was found that they are valid only under certain specific conditions.

Hypohydration increases physiological strain during exercise in the heat. A loss of only 1% body weight water compared to euhydration causes an increase in core temperature during exercise in normothermic and warm environments (8). Hertzman and Ferguson (24) were the first to describe hypohydration during heat stress as a "failure of the thermoregulatory system". The addition of hypohydration to the stress further reduces endurance and influences the thermoregulatory control systems, either through associated changes in blood volume (44) or through accompanying changes in plasma osmolality (21). The cardiovascular system is also affected by hypohydration during exercise in the heat. First, hypohydration results in an increase in HR to compensate for the fall in stroke volume. Second, hypohydration reduces cutaneous blood flow; thus, the potential for dry heat exchange (by convection and radiation) between the body and the environment is lowered, impairing heat dissipation from the body (58). In 1960, Senay (59) suggested that the increased core temperature in hypohydrated individuals is necessarily the consequence of reduced heat transfer. In 1995, Sawka et al. (58) concluded that during exercise-heat stress, hypohydration compared to euhydration accelerates exhaustion from heat strain at a lower rectal temperature (T_{re}).

Hypohydration is usually associated with either a reduced or unchanged sweat rate ($\dot{m}_{sw}$) (58). When no change in $\dot{m}_{sw}$ was reported during dehydration in a warm

climate at a given metabolic rate, T_{re} was elevated reflecting higher strain and delayed $\dot{m}_{sw}$ threshold (57). Numerous investigators had attributed the higher core temperatures that accompany thermal hypohydration to either failure of the sweating response (8, 18) or to a redistribution of blood flow from the cutaneous regions. Some studies showed that different levels of hypohydration affect the sweating mechanism to different degrees (9, 56, 57). Montain et al. (38) found that the threshold temperature for sweating increased with hypohydration level, unlike sweating sensitivity, which decreased. In that study, the exercise intensity when combined with hypohydration increased sweating sensitivity, but did not alter the sweating threshold temperature.

Physiological responses to exercise-heat stress may be different between genders because of several factors. When compared to men, women generally have lower cardiorespiratory fitness, higher percentage of body fat, lower body weight, lower body surface area, and higher surface area-to-mass ratio (A_D/wt) (32, 48, 50, 64). In addition, hormonal fluctuations of estrogen and progesterone associated with the menstrual cycle may alter women's performance and tolerance to exercise-heat-stress (53, 55).

Several investigators have shown that women thermoregulate less effectively than men when exposed to acute-heat stress and exercise (10, 35, 60, 61). In her review of 1978, Nunneley (46) concluded that under the same thermal load, women had higher core and skin temperatures, higher heart rates (HR), and lower sweating rates ($\dot{m}_{sw}$) when compared to men. However, these physiological differences were mainly attributed to lifestyle related inequalities in fitness and acclimation. Although heat acclimation eliminated many of these gender-related physiological differences, sweat rate still remained lower for women (1, 66). Stephenson and Kolka (62) suggested that the general belief that women were less tolerant to heat strain was based on comparatively unmatched genders, mainly aerobically fit men to relatively unfit women. Some studies found that when genders were matched for aerobic fitness and physical characteristics, many of the physiological differences were narrowed, especially during light exercise (2, 12, 23, 35). In 1995, Sawka et al. (58) concluded that if men and women were matched for aerobic fitness, then they would have similar heat tolerances and body temperature responses during exercise in the heat. Nevertheless, Stephenson and Kolka (62) argued that most of the studies that compared responses of men and women were not controlled for menstrual cycle phase and, as a consequence, were limited in their conclusions.

There were three purposes for this study. The first purpose was to develop a simple physiological strain index (PSI) to be used in hot environments. The index should be capable of indicating heat strain on-line, and analyzing existing databases, and should be sensitive enough to differentiate between similar exposures which differ in one variable (e.g., clothing, metabolic rate, climate). The second purpose was to examine the PSI ability for assessing and categorizing heat strain at different combinations of hypohydration level and exercise intensity, and to evaluate the interaction between PSI and $\dot{m}_{sw}$ for these experimental conditions. The third purpose

was to examine the ability of PSI as a tool to evaluate and assess gender heat strain differences at various exercise intensities and climatic conditions. In addition, we aimed to evaluate the interactions between PSI and $\dot{m}_{sw}$ or relative exercise intensity from these same experiments.

METHODS

The new PSI was developed from databases collected from subjects who differed in their physical fitness and heat-tolerance, and was further evaluated for independent databases consisting of different combinations of climates, metabolic rates, clothing ensembles, hydration levels, and gender.

STUDY I

Two database sets were used in study I. The first served to develop the new index, while the second database, taken from an independent report (39), was used to validate the newly developed index.

Subjects

One hundred healthy, young men at different levels of fitness and heat acclimation volunteered to participate in the study. The physical characteristics of the subjects were as follows (mean ± SE): age 20±3 yr; height 178±10 cm; weight 74.6±10.5 kg; body surface area 1.92±0.15 m^2. Ten subjects had a medical history of heat-related disorders. Before participation, each subject underwent a medical examination that included a complete medical history, electrocardiogram at rest, urine analysis, and blood screening biochemistry. Subjects were informed as to the nature of the study and potential risks of exposure to exercise in a hot climate. All subjects signed a form of consent.

Protocol

Twenty-four hours prior to exposure, subjects were in good medical condition and had not taken any prescribed, unprescribed medication or alcohol. The subjects wore only shorts and sport shoes, and performed exercise in a hot/dry climatic condition of 40°C, 40% relative humidity (RH) for 120 min. Following 10 min of rest, the subjects began walking on a treadmill at a constant speed of 1.34 $m \cdot sec^{-1}$ at a 2% grade. A number of experiments were terminated before the scheduled 120 min time, when a subject voluntarily withdrew, when a subject's T_{re} reached 39°C, or when HR exceeded 180 bpm for 3 consecutive min. Termination at any time was according to the attending physician's decision. The estimated oxygen consumption ($\dot{V}O_2$) for all subjects during exercise was 1$L \cdot min^{-1}$ [~25-30% of mximal oxygen consumption ($\dot{V}O_{2max}$)].

Measurements

During the exposures, HR and T_{re} were continuously monitored and recorded at 1 min intervals. T_{re} was measured by a thermistor probe inserted 10 cm beyond the anal sphincter (Yellow Spring Instruments - series 401). Heart beats and HR were monitored and recorded on-line through bipolar chest leads using Polar belt electrodes (Polar CIC, Inc. USA). Sweat rate was calculated from changes in body weight before and after the exercise (Shinko Denski ±5 gr) corrected for water intake and urine. The subjects were encouraged to drink cold tap water ad libitum.

Calculations

Heat strain indices (HSI and CHSI) were calculated as suggested by Belding and Hatch (4) and Frank et al. (11), respectively. Maximum evaporative heat exchange (E_{max}) and the required evaporative cooling (E_{req}) used in the HSI index were calculated according to Givoni and Goldman's (15) original equations, with algorithm modifications published by Pandolf et al. (49). All calculations of the normalized areas under the T_{re} curve at any time (AUC_{Tre}), normalized by the initial data point, was calculated according to the trapezoidal rule as follows (5):

$$AUC_{Tre}=\Delta t\,(0.5T_{re0}+T_{re1}+T_{re2}...+T_{ren-1}+0.5T_{ren})\cdot T_{re0}^{-1} \tag{1}$$

where Δt is the time interval for measuring T_{re} and T_{re0} is the initial T_{re}.

Similarly, the area under the HR curve at any time point (AUC_{HR}), normalized by the initial data point, was calculated as follows:

$$AUC_{HR}=\Delta t\,(0.5HR_0+HR_1+HR_2...+HR_{n-1}+0.5HR_n)\cdot HR_0^{-1} \tag{2}$$

where HR_0 is the initial HR.

Validation of the developed index was done with a database from Montain et al. (39), within the range of HR=68-171 bpm, and T_{re} =36.4°-39.4°C. Seven healthy male subjects [age 21±1 yr, body weight 80.1±4.0 kg, body surface area 2.0±0.08 m^2, and $\dot{V}O_{2max}$ 52±2 $ml\cdot kg^{-1}\cdot min^{-1}$] walked on a treadmill ($\dot{V}O_2$ ~1.5 $1L\cdot min^{-1}$) for 180 min while wearing partial protective clothing ensembles consisting of pants and coat (clo=1.3 and im=0.55 at wind speed 2.2 $m\cdot sec^{-1}$) in both hot-dry (43°C, 20% RH) and hot-wet

(35°C, 50% RH) climatic conditions. In addition, we used this database to compare other heat strain indices (HSI, CHSI) to the newly developed index.

STUDY II

In this study, the newly developed PSI was applied to two databases (37, 38). The first database produced different levels of dehydration by having volunteers drink different volumes of fluid during prolonged exercise in the heat (37). The second database, taken from an independent study, examined the HR, core temperature, and sweating response to different combinations of hypohydration level and exercise intensity (38).

Protocol 1

Evaluation of PSI for different levels of dehydration during prolonged exercise was done using a database from Montain and Coyle (37), within the range of HR=53-175 bpm, T_{re}=36.8°-39.7°C and T_{es}=36.4°-39.2°C. Eight endurance-trained male cyclists (age 23±3 yr, body wt 72.2±11.6 kg, and $\dot{V}O_{2max}$ 66.2±7.6 ml·kg^{-1}·min^{-1}) cycled at a power output eliciting 62%-67% $\dot{V}O_{2max}$ for 120 min in a warm environment (33°C, 50%RH). Each subject completed four experimental exposures while ingesting different volumes of fluid during exercise: no fluid, or a volume that replaced 20%, 50%, and 80% of the fluid lost in sweat [resulting in 4.2%±0.1, 3.4%±0.1, 2.3%±0.1, and 1.1±0.1% body weight loss (BWL), respectively, after 120 min cycling].

Protocol 2

Nine healthy young acclimated men participated in the study (38). The physical characteristics of the subjects were as follows (mean ± SE): age 24±2 yr, height 176±3 cm, body wt 81.7±4.5 kg, and $\dot{V}O_{2max}$ 57±2 ml·kg^{-1}·min^{-1}. Subjects completed nine experimental exposures of 50 min exercise in warm climate conditions (30°C, 50% RH). The exposures consisted of exercise on a treadmill at three intensities: 25%, 45% and 65% of $\dot{V}O_{2max}$, when euhydrated or hypohydrated by 3% and 5% of the subjects baseline body weight. Hypohydration was achieved on the day before each trial using a standardized exercise-heat protocol. For the 5% body weight loss (BWL) trials, subjects performed 2-3 hours of exercise in the morning, in addition to an afternoon exercise session. A number of experiments were terminated before the scheduled 50 min exposure time during the 65% $\dot{V}O_{2max}$ trials, when a subject voluntarily withdrew, when a subject's esophageal temperature (T_{re}) reached 39.5°C, or when HR exceeded 90% of HR_{max} for 3 consecutive min.

In both protocols, T_{re} was measured from a thermistor (model YSI 401, Yellow Springs Instruments) inserted 10 cm past the anal sphincter. Esophageal temperature (T_{es}) was measured by a thermocouple in a catheter placed at heart level, and was continuously monitored and recorded. HR was monitored and recorded at 10 min

intervals with a telemetry system. In addition, in the second protocol local sweating rate ($\dot{m}_{sw}$) of the upper arm was calculated from a continuously ventilated dew-point sensor within a 15.9 cm^2 capsule (37).

Calculations

The PSI was calculated either using T_{es} (PSI_{Tes}) or T_{re} as suggested by Moran et al. (43) as follows:

$$PSI=5(T_{ret}-T_{re0})\cdot(39.5-T_{re0})^{-1}+5(HR_t-HR_0)\cdot(180-HR_0)^{-1} \quad (3)$$

where T_{re0} and HR_0 are the initial T_{re} and HR, and T_{ret} and HR_t are simultaneous measurements taken at any time.

Sweating sensitivity was calculated as the slope of the regression line representing min $\dot{m}_{sw}$ and T_{es} values obtained during the linear phase of the exercise transient (<20 min of exercise). Threshold for active thermoregulatory sweating was defined as the T_{re} when $\dot{m}_{sw}$ exceeded 0.06 $mg\cdot cm^2\cdot min^{-1}$ and began to progressively increase sweating above resting values (37).

STUDY III

The purpose of this study was to see if gender differences during exercise-heat stress can be assessed by the PSI.

Subjects

Two groups of eight men each and a group of nine women (W) participated in this study (42). The two groups of men were divided according to their maximal oxygen consumption ($\dot{V}O_{2max}$) The first group of men (M) was matched to the women of similar $\dot{V}O_{2max}$ [46.1±2.0 and 43.6±2.9 $ml\cdot min^{-1}\cdot kg^{-1}$ (P>0.001), respectively]. The second group of men (MF) was significantly (P<0.001) more fit than either M or W with $\dot{V}O_{2max}$ of 59.1±1.8 $ml\cdot min^{-1}\cdot kg^{-1}$. All subjects were young volunteers and their physical characteristics are summarized in Table 1. Before experimentation, each subject underwent a medical examination that constituted a complete medical history, electrocardiogram at rest, urine analysis, and sequential multichannel autoanalyzer-12 blood screening biochemistry. None of the participants had a history of medical disorders for at least 6 months prior to the study. All subjects were informed as to the nature of the study and potential risks of exposure to exercise in a hot climate, and all signed a volunteer consent form.

Table 1. Mean (±SE) physical characteristics for the subjects of Study III

	n	Age yr	Weight kg	Height cm	A_D m^{-2}	$\dot{V}O_{2max}$ $ml\cdot min^{-1}\cdot kg^{-1}$	BMI $A_D\cdot wt^{-1}$
Women (W)	9	25±1	62.7±3.4	169±1.6	1.71±0.04	43.6±2.9	0.028±0.00
Men (M)	8	23±1	71.5±2.8	175±2.5	1.86±0.04*	46.1±2.0	0.026±0.01
Men-fit (MF)	8	25±1	65.9±2.9	174±3.4	1.79±0.05	59.1±1.8†	0.027±0.00

A_D = body surface area; BMI = body mass index.
* Significant difference between W and M (P<0.03).
† Significant difference between MF and M or W (P<0.001).

Protocol

The study was conducted in the climatic chamber at the Heller Institute of Medical Research, Sheba Medical Center, Tel Hashomer, Israel. The experimental protocol was reviewed and approved by the Institution's Ethical Committee of Investigations Involving Human Subjects.

Prior to these experiments, the subjects underwent a thorough heat acclimation procedure. The acclimation procedure consisted of exposure to 40°C, 40% RH in a climatic chamber, for 2 hours daily for 10 consecutive days. During the exposure, the subjects exercised on a treadmill elevated by 3% ($\dot{V}O_2$= 1.2 $L\cdot min^{-1}$) at a speed of 1.34 $m\cdot s^{-1}$. They were dressed only in shorts and sport shoes (women with bras as well). Significantly lower (P<0.01) values of T_{re} and HR were found in all subjects at the end of the last acclimation exposure when compared to the end of the first acclimation exposure. On the last day of the acclimation procedure, all subjects performed a $\dot{V}O_{2max}$ test on a treadmill in a comfortable climate (20°C, 50% RH) (63).

Table 2. Experimental combinations of climate and exercise intensity for Study III.

	Exposure
Exercise intensity	Low (~ 300W) Moderate (~ 500W) High (~ 650W)
Climate	Comfortable [(20°C, 1.16kPa (50%RH)] Hot-wet [(35°C, 3.93kPa (70%RH)] Hot-dry [(40°C, 2.58kPa (35%RH)]

After acclimation, all subjects were exposed to nine experimental exposures that consisted of different combinations of exercise intensity and climatic condition (Table 2). The combinations were assigned at random to the subjects, but were controlled to eliminate order effects. The work consisted of walking on a treadmill at a speed of 1.34 $m \cdot s^{-1}$, with no grade at the low ($\dot{V}O_2$ ~0.9 $L \cdot min^{-1}$) work load, and with 5% and 10% grade at the moderate ($\dot{V}O_2$ ~1.4 $L \cdot min^{-1}$) and the high ($\dot{V}O_2$ ~1.9 $L \cdot min^{-1}$) work load, respectively. Each climatic chamber exposure contained 10-min rest period followed by 60-min exercise. However, data from the MF group at the low work intensity in the comfortable climate were not analyzed because not all of the subjects were available for testing. Each exercise intensity was combined with each climate, providing nine experimental conditions.

Measurements

During these exposures, T_{re} and HR were monitored and recorded every 5 min. The T_{re} was measured by a thermistor probe inserted 10 cm beyond the anal sphincter (Yellow Spring Instruments series 401). HR was measured and monitored online through bipolar chest leads using Polar belt electrodes (Polar CIC). Sweat rate,

oxygen consumption ($\dot{V}O_2$), and skin temperature (T_{sk}) were also monitored during these experimental exposures.

Sweat rate was calculated from body weight differences using a precision electronic scale (±10 g) and adjusted precisely (±5 ml) after measurement of water intake and urine output. The subjects were encouraged to drink cold tap water ad libitum (0.5-1.5 L). To determine metabolic rate, oxygen consumption was measured toward the end of each experimental exposure. Expiratory gases were sampled and analyzed every 15 s by an automatic metabolic cart (CPX - MGC, Medical Graphic) with the mean value for 2 min used for calculations. T_{sk} was measured every 5 min by skin thermistors (Yellow Spring Instruments series - 409) at three locations (chest, arm and leg) and mean-weighted T_{sk} was calculated according to Burton (7).

Calculations

The relative oxygen consumption ($\%\dot{V}O_2$) for each subject during each exercise intensity at the different climates was computed from the maximal oxygen consumption ($\dot{V}O_{2max}$) performed in a comfortable climate as follows: $\%\dot{V}O_{2max} = 100(\dot{V}O_2/\dot{V}O_{2max})$.

RESULTS

STUDY I

The first study served to develop a simple to use PSI. After analyzing the different physiological parameters and the literature, we chose T_{re} and HR, which depict the combined strain resulting from the cardiovascular and the thermoregulatory systems. It was assumed that the maximal acceptable rise of T_{re} during exposure to heat stress from normothermia to hyperthermia is 3°C (based on maximal change from 36.5°C to 39.5°C). Similarly, the maximal allowable elevation of HR was assumed to be 120 bpm (based on maximal change from 60 bpm to 180 bpm). Based on these values, an integral stress index (ISI) may be fitted as follows:

$$ISI=10(AUC_{Tre}\cdot T_{re0}/3+ AUC_{HR}\cdot HR_0/120)t^{-1} \qquad (4)$$

where 10 is an arbitrary constant introduced to increase the numerical values predicted by the model, and t is the total exposure time (min).

The response of the ISI curve was similar for T_{re} and HR dynamics, unlike the CHSI curve, which represented a mirror image pattern to T_{re} and HR dynamics as

depicted in Fig. 1. The ISI described the strain on-line on a scale of 0-15, whereas the CHSI rated the strain from 0 to a few hundreds or thousands depending on the length of the exposure time. However, it can be seen that both indices continued to rise after 120 min (i.e., during the recovery period) while T_{re} and HR decreased (Fig. 1).

In order to evaluate heat stress on a universal scale of 0-10 and to overcome the limitations of continually getting higher values during rest or recovery periods, we constructed an index which enabled us to calculate the physiological strain on-line at any time. The index was based on the same maximal rise values for T_{re} and HR as described above for the ISI index (according to the Human Use Review Committee Limits). Thus, the following normalized PSI was suggested (eq. 3):

$$PSI=5(T_{ret}-T_{re0})\cdot(39.5-T_{re0})^{-1}+5(HR_t-HR_0)\cdot(180-HR_0)^{-1}$$

where T_{ret} and HR_t are simultaneous measurements taken at any time. T_{re} and HR, which depict the combined load of the thermoregulatory and the cardiovascular systems, were assigned with the same weight by using a constant of 5. Thus, the index was scaled to a range of 0-10 within the limits of the following values: $36.5 \leq T_{re} \leq 39.5$°C and $60 \leq HR \leq 180$ bpm.

Figure 1. Integral strain index (ISI) and cumulative heat strain index (CHSI) applied to rectal temperature (T_{re}) and heart rate (HR) data obtained from 1 subject. Note that after 120 min, although HR and T_{re} decrease, CHSI and ISI continue to rise.

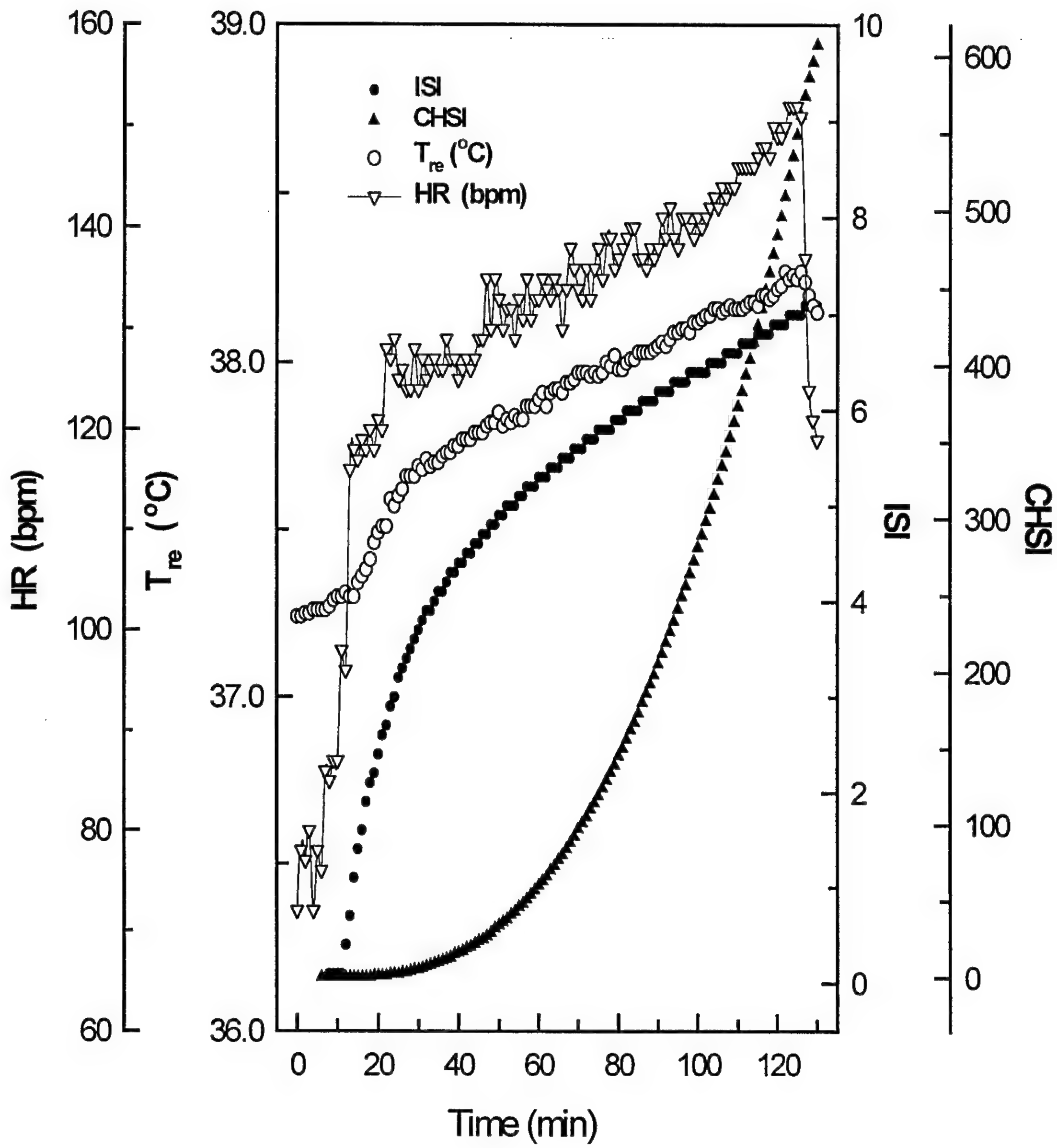
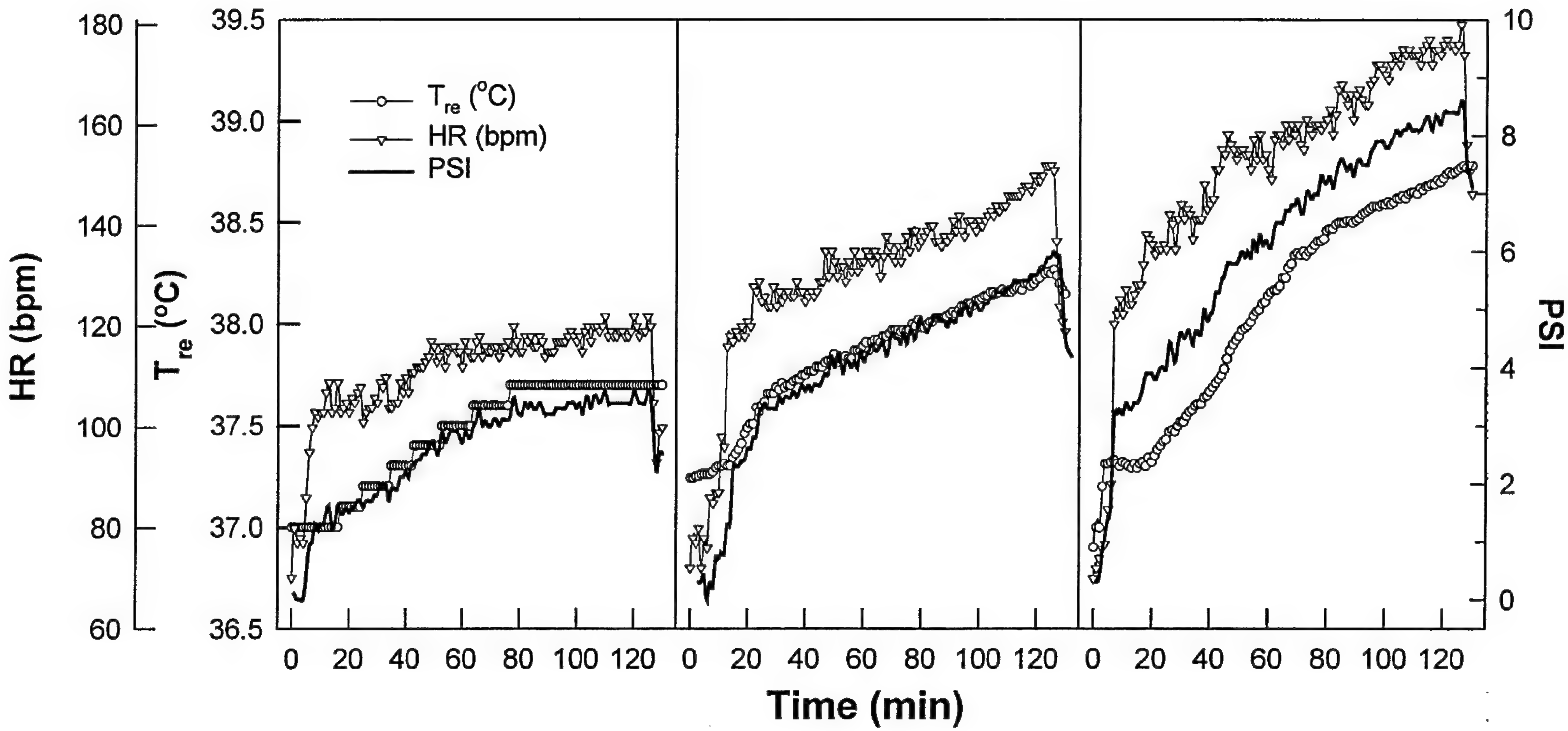


Table 3. Evaluation and categorization of different heat strains by PSI.

Strain	PSI
no/little	0
	1
	2
low	3
	4
moderate	5
	6
high	7
	8
very high	9
	10

This index was applied to the data obtained from the 100 subjects performing exercise in the heat; concomitantly, a new scale to evaluate physiological heat stress was suggested (Table 3). Since the subjects were not a homogeneous group and varied in their physical fitness, acclimation status and tolerance to heat, data analysis was applied individually. Figure 2 depicts data obtained from 3 different subjects exposed to the same climatic conditions (40°C, 40% RH), but at different strain levels during the heat exposure. Mild physiological strain, rated as 3-4, was observed for the first subject (left panel), moderate strain marked as 4-6 is presented for the second subject (middle panel), and high physiological strain, which linearly increased with exposure time and rated as 8.5 after 120 min, is seen for the third subject (right panel).

Figure 2. Physiological strain index (PSI) (solid line), calculated from T_{re} (o) and HR (∇) applied to 3 subjects exposed to the same heat stress (40°C, 40% RH, 1.34 m·sec^{-1} at a 2% grade).



A separate database was applied to test the validity of the present index. This database was compiled from results obtained during 180 min of exposure under two combinations of clothing ensembles, and two different climatic conditions (hot/dry and hot/wet) at various work loads (39). A comparison of T_{re} and HR data, obtained at moderate work, between hot/dry and hot/wet climatic conditions is depicted in Fig. 3. Significantly higher values of T_{re} and HR were observed in the hot/dry climatic condition ($P<0.05$).

Three indices (HSI, CHSI, and PSI) were applied to the same T_{re} and HR database presented in Fig. 3. The CHSI and PSI rated the exposures in the hot/dry climate at higher physiological strain for the subjects (Fig. 4). In contradiction, the HSI used in Montain et al. study (39) rated the exposures in the hot/wet climate with higher values than the hot/dry climate (HSI = 105±3.1 and 95±1.8, respectively).

Figure 3. Comparison between T_{re} dynamics in hot/dry [o] and hot/wet [•] climates, and between HR dynamics in hot/dry [∇] and hot/wet [▼] climates. Values (mean±SE) obtained from 7 subjects exposed to moderate exercise (425 watt) wearing MOPP gear (39).

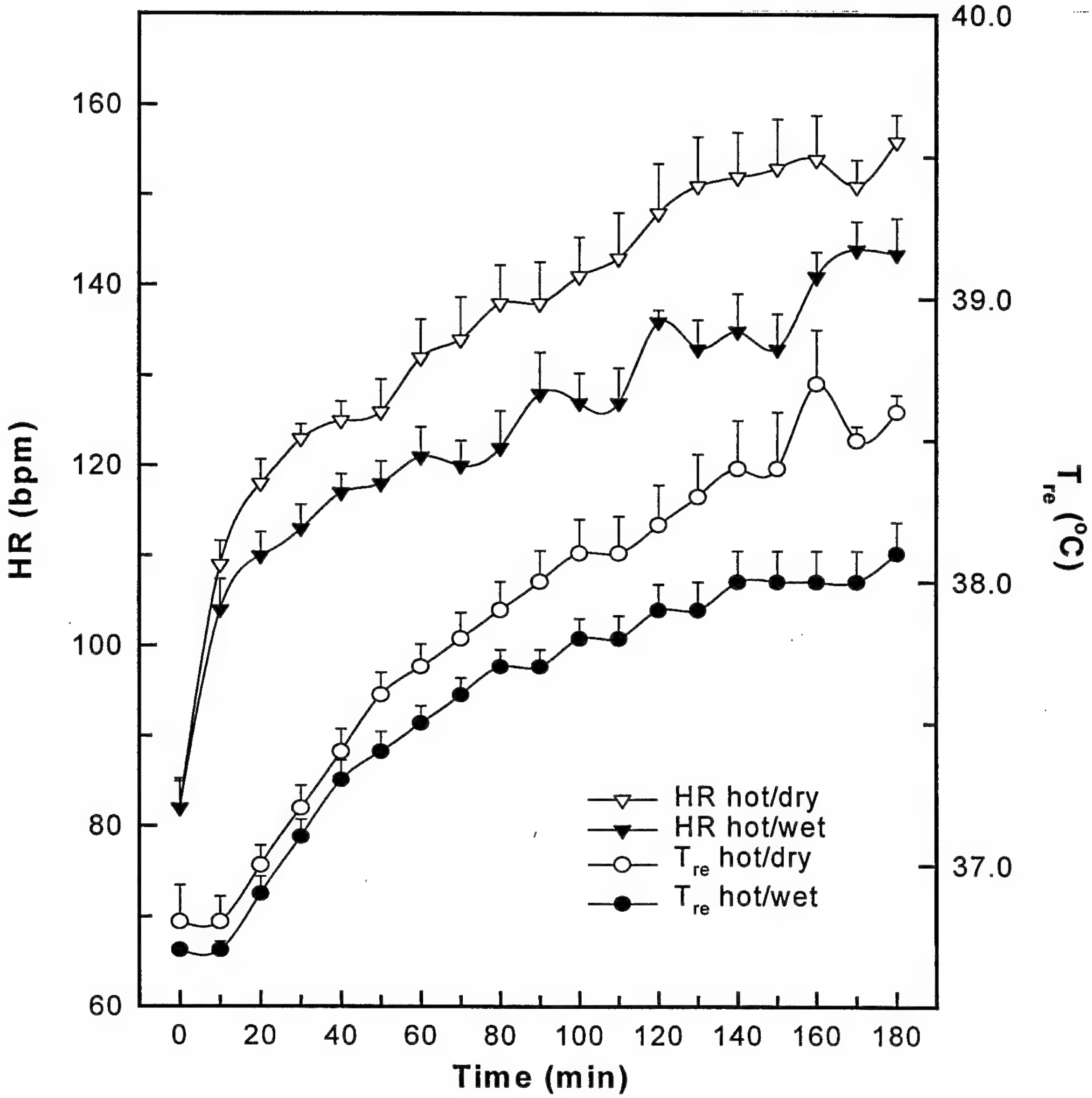
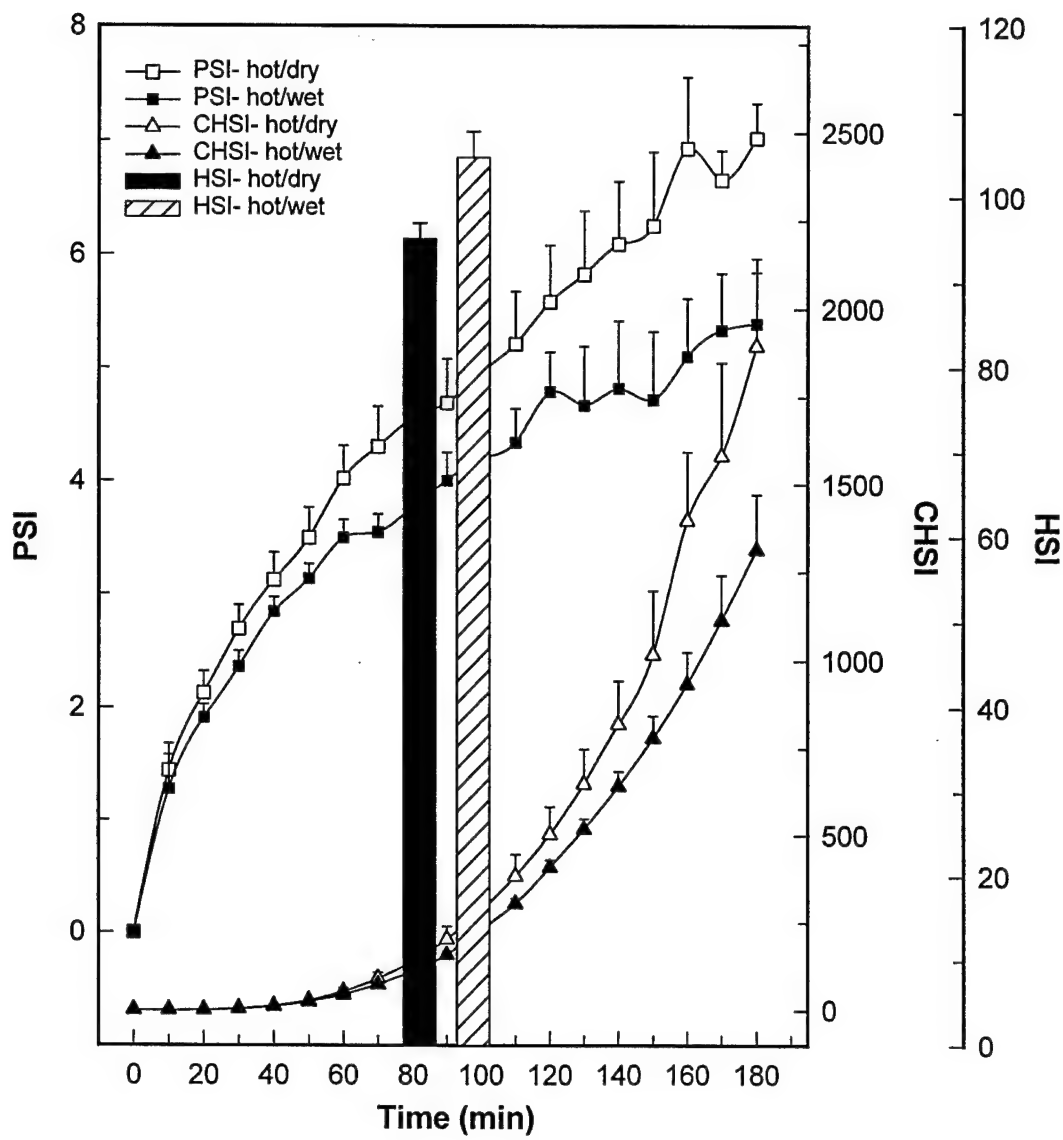


Figure 4. Comparison between HSI, CHSI, and PSI applied on Montain et al. data base (39). Note that HSI rated the hot/wet climate as the higher strain, in contradiction to CHSI and PSI which rated the hot/dry climate as the higher strain.



STUDY II

The purpose of this study was to examine the PSI ability for assessing and categorizing heat strain at different combinations of hypohydration level and exercise intensity. In addition, we aimed to evaluate the interaction between PSI and $\dot{m}_{sw}$ for these experimental conditions.

Database I

Generally, T_{re} and T_{es} were elevated in proportion to the magnitude of the hypohydration levels, and the four trials were significantly different from each other ($P<0.05$), with the exception of the 3.4% and 4.2% BWL exposures (Fig. 5). Similarly, HR increased progressively during exercise at the different levels of hypohydration. However, at 120 min of exercise, HR was not significantly different between the exposures of 1.1% and 2.3% BWL, and the 3.4% and 4.2% BWL (Fig. 5).

The PSI correctly discriminated between combinations of exercise intensity and hypohydration level for these trials. A comparison of PSI at the four levels of dehydration induced by ingesting different volumes of fluid during exercise is depicted in Fig. 6 and Table 4. Significantly higher values of PSI were observed with increasing hypohydration level ($P<0.01$). As a consequence of the significantly higher values of T_{re} when compared to T_{es} ($P<0.01$), there were also significantly higher values of PSI for T_{re} than for T_{es}.

PSI rated the strain in rank order according to the hypohydration level [from 6.5 to 8.7 (for 1.1 to 4.2% BWL, respectively)]. Categorization of the strain was done according to Study I (Table 3). However, the Borg scale (6) for subjective rating of perceived exertion (RPE) revealed a similar strain categorization as with PSI (Table 4). The RPE increased with hypohydration level during the 120 min exposures and was significantly different across all trials ($P<0.05$), with the exception of 1.1% and 2.3% BWL exposure. The mean RPE categorized the four levels of hypohydration as "Somewhat Hard" to "Very Hard", ranging from 13.4% to 17.6% (for 1.1% to 4.2% BWL, respectively).

Figure 5. The PSI [–], calculated from T_{re} [O] and HR [∇], applied to mean values obtained from 8 subjects exposed to heat stress (33°C 50% RH, 65% $\dot{V}O_{2max}$) at 4 different levels of hypohydration (1.1%, 2.3%, 3.4%, and 4.2% BWL).

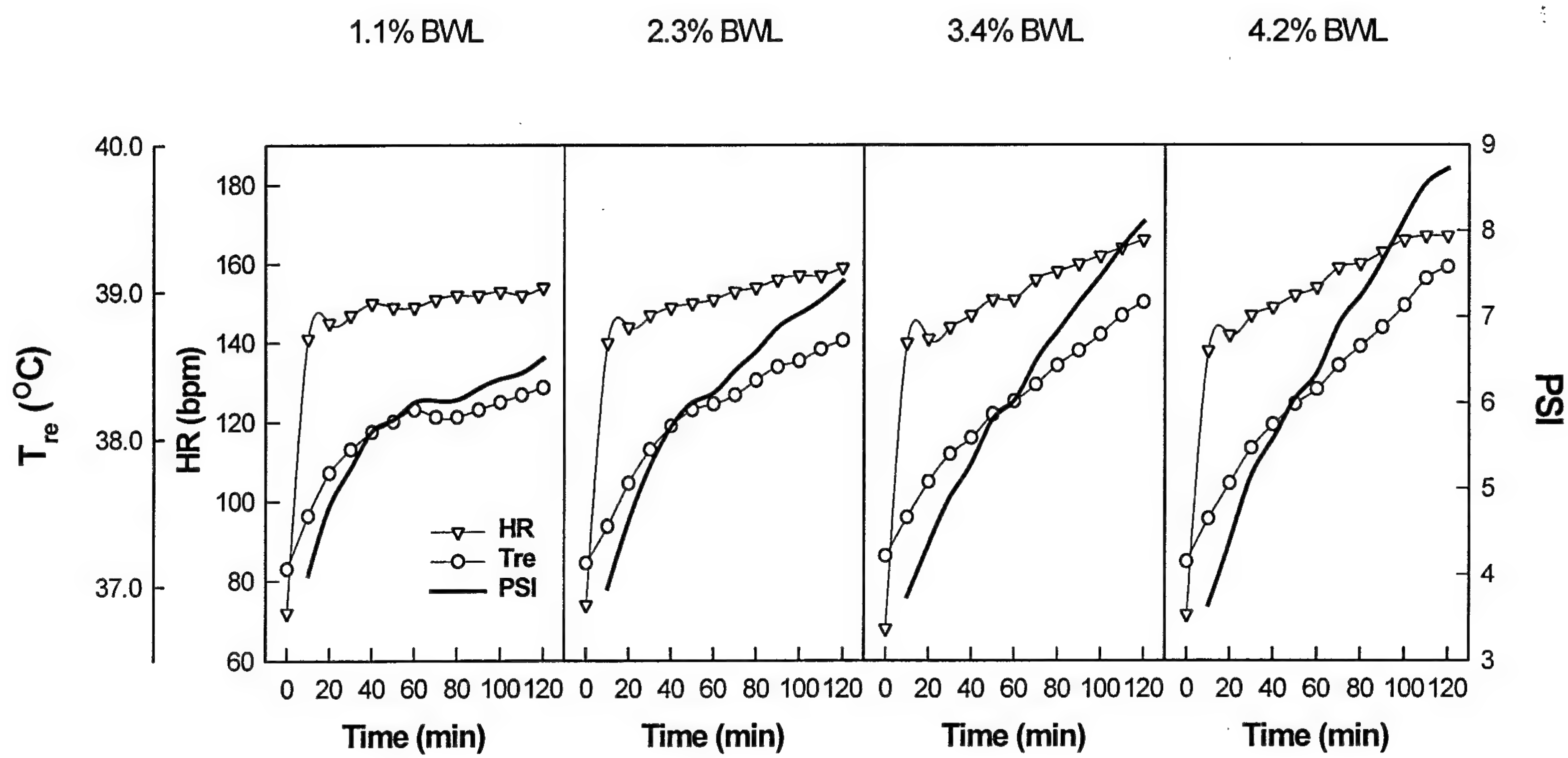


Figure 6. PSI calculated from T_{re} (left panel) and T_{es} (right panel) on database of Montain and Coyle (37). Values obtained from 8 subjects exposed to 4 different levels of hypohydration (1.1%, 2.3%, 3.4%, and 4.2% of BWL) during exercise.

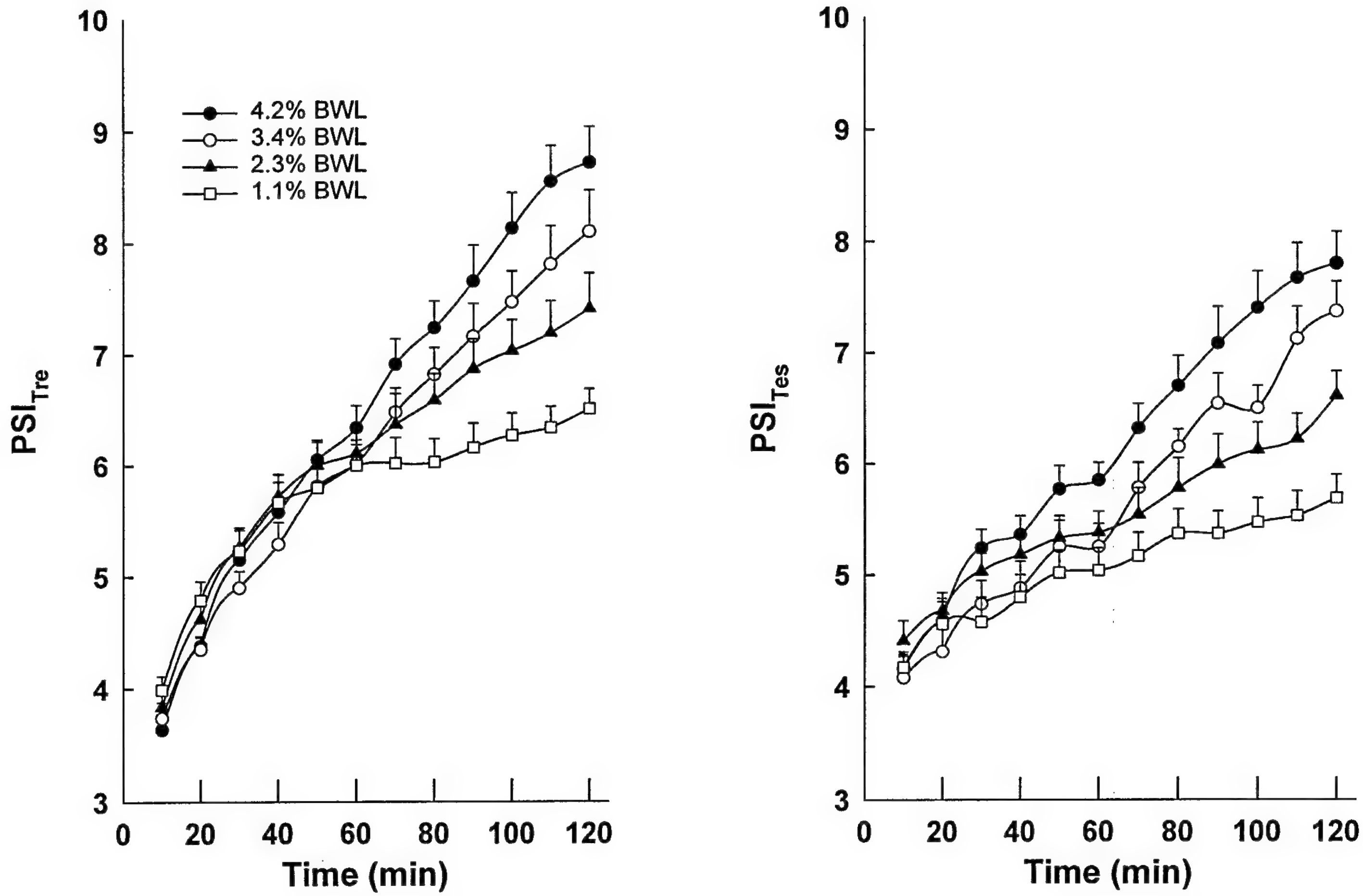


Table 4. Evaluation and categorization of different strains by PSI and RPE of 8 subjects after 120 min exposure to heat stress (30°C 50% RH, 65% $\dot{V}O_{2max}$) at different hypohydration levels.

Hypohydration (%BWL)	**PSI** (units)	(strain)	**RPE** (units)	(strain)
1.1	6.5±0.8	Moderate	13.4±0.5	Somewhat hard
2.3	7.4±0.3	High	14.1±0.6	Somewhat hard-Hard
3.4	8.1±0.4	High	15.6±0.8	Hard
4.2	8.7±0.3	Very high	17.6±0.3	Very hard

Database II

The HR, T_{re} and T_{es} dynamics during these experimental exposures are presented in Figs. 7 and 8. Generally, at the same exercise intensity HR, T_{re} and T_{es} values were higher with increasing levels of hypohydration. At the low exercise intensity (25% $\dot{V}O_{2max}$), HR values were significantly less than for the other two intensities (45 and 65% $\dot{V}O_{2max}$) across all hydration levels ($P<0.05$). Similarly, HR values at 3 and 5% BWL for the moderate intensity were not significantly different from the euhyhdration values at the high exercise intensity (Fig. 7). When compared to simultaneous measurements of T_{es}, all T_{re} values were significantly higher (~0.1-0.4°C; $P<0.01$). Analyzing the T_{re} and T_{es} dynamics during all the exposures revealed a pattern in which the low exercise intensity at 5% BWL overlapped with the high intensity during euhydration (Fig. 8).

Figure 7. HR dynamics (mean±SE) of all subjects who participated in the 9 experimental exposures consisting of 3 exercise intensities (25%, 45%, and 65% $\dot{V}O_{2max}$) and 3 hydration levels (euhydration and hypohydration at 3% and 5% of body weight). *Drop due to subject attrition.

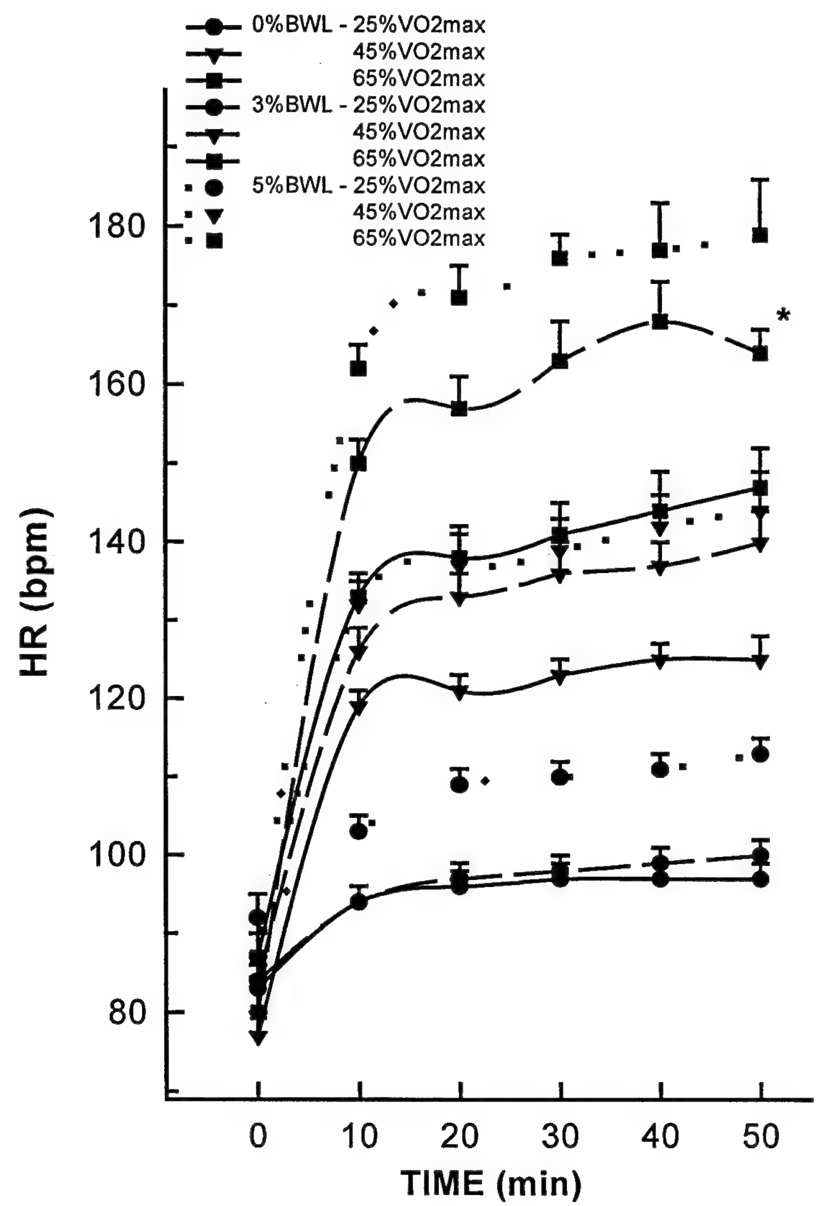
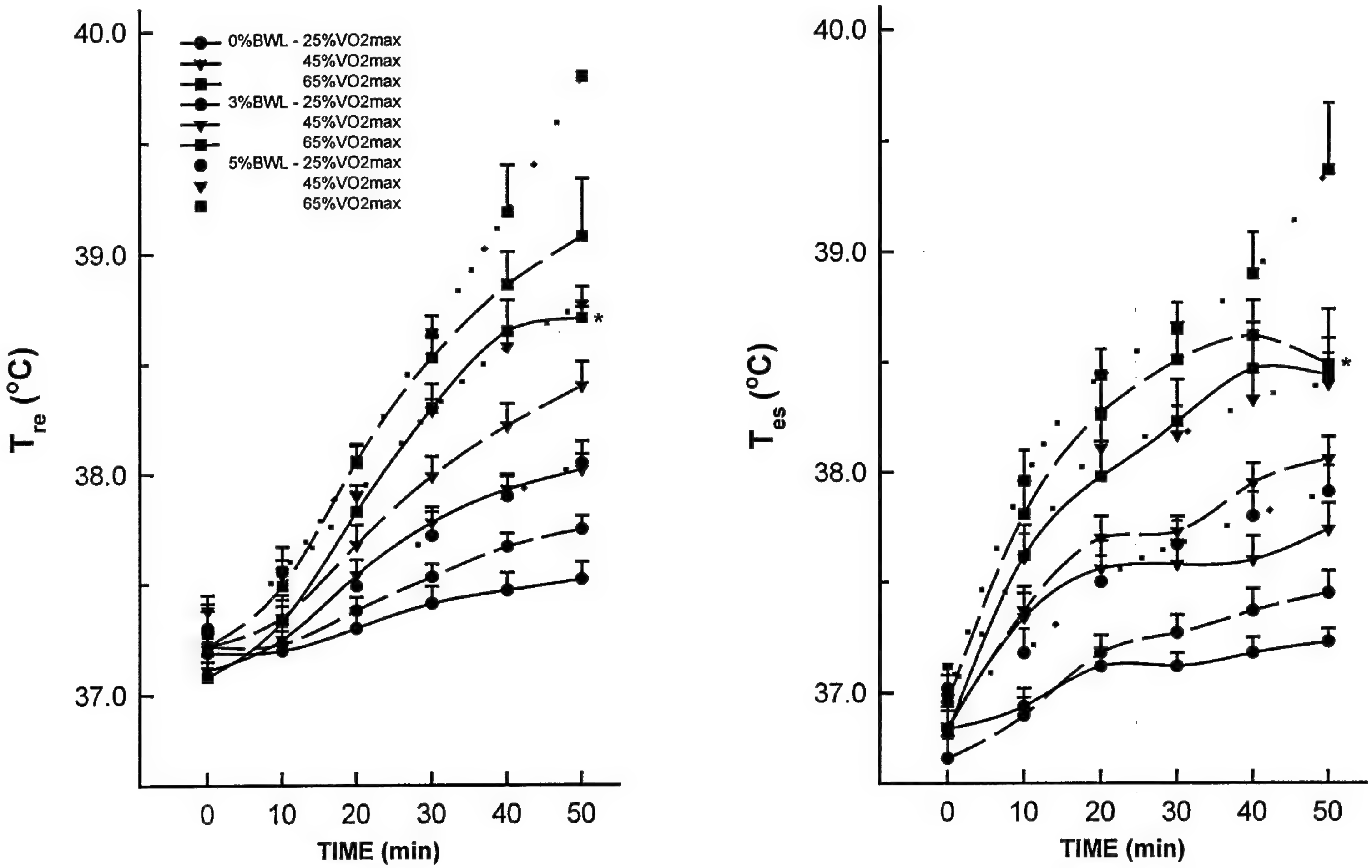


Figure 8. T_{re} (left panel) and T_{es} (right panel) dynamics (mean±SE) of all subjects participated in the 9 experimental exposures. * Drop due to subject attrition.



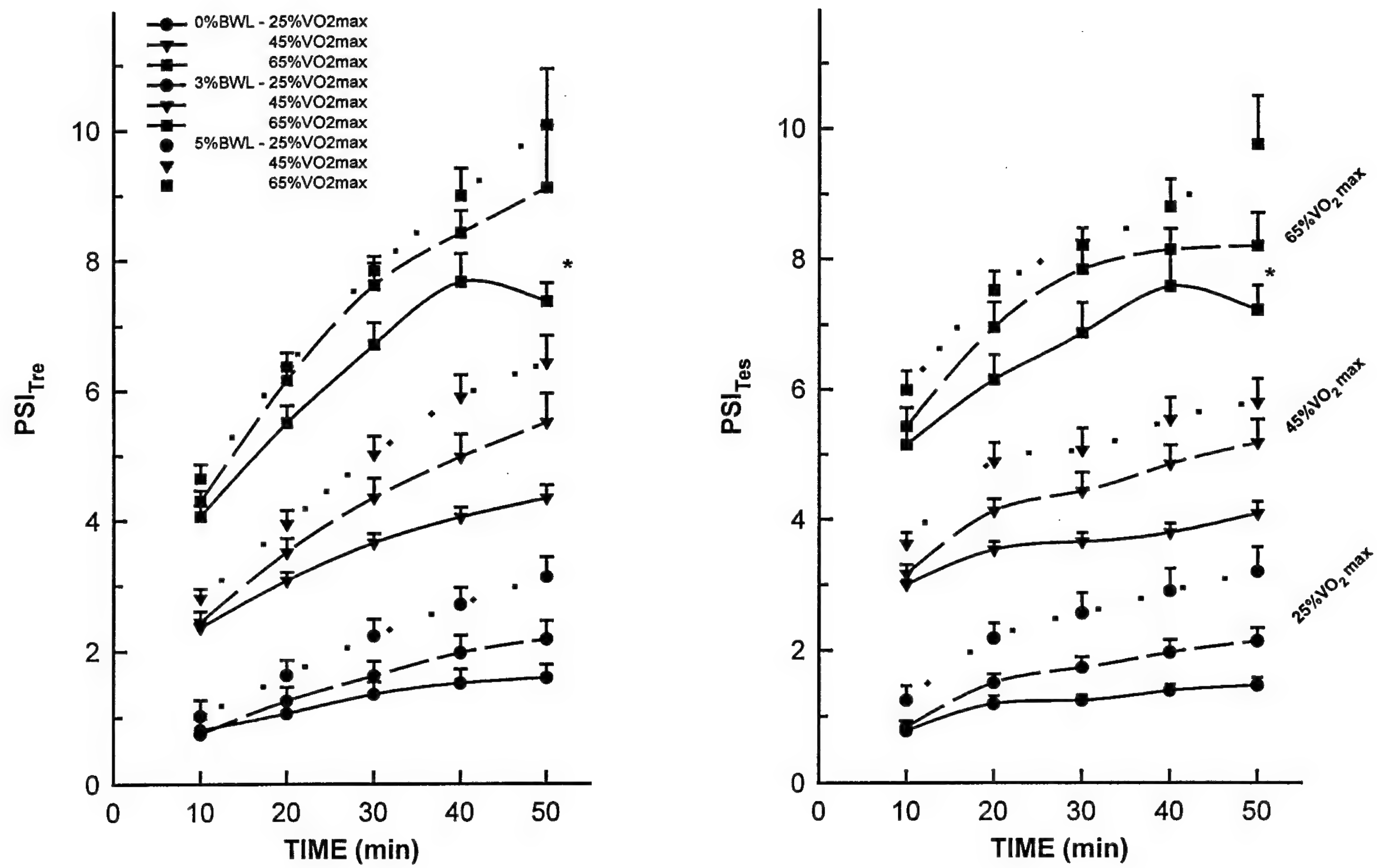
In Fig. 9, PSI was applied to HR and T_{re} (left panel), and HR and T_{es} (right panel) collected from the nine subjects performing the nine experimental combinations (38). PSI was found to be correlated (r=0.99) with exercise intensity and with hypohydration level using either T_{re} or T_{es}. PSI succeeded in clearly differentiating between all the exposures on a scale within the 0-10 range. There were no significant differences between PSI calculated using T_{re} or T_{es} at 25% and 45% $\dot{V}O_{2max}$. However, PSI obtained at 65% $\dot{V}O_{2max}$ from T_{re} were significantly higher than the PSI obtained from T_{es} ($P<0.01$).

PSI categorized the heat strain in rank order according to the combined exercise intensity and hydration level (Table 5). In general, the euhydration exposures were ranked as little or low strain with values of 1.6±0.2 to 3.1±0.3. The 3% BWL exposures were ranked as moderate strain and ranged from 4.3±0.2 to 6.4±0.4, while the 5% BWL exposures were categorized with high and very high strains, ranging from 7.4±0.3 to 10.0±0.9.

Table 5. Calculated PSI from measured HR and T_{re} obtained from 9 subjects exercised in the heat (36°C, 50% RH) after 50 min at different exercise intensities (25%, 45% and 65% $\dot{V}O_{2max}$) and different hydration levels (euhydration and hypohydration at 3% and 5% body weight).

Work intensity ($\%\dot{V}O_{2max}$)	**Hydration** (%BWL)	**PSI** (units)	(strain)*
25	0	1.6±0.2	Little
	3	2.2±0.3	Little
	5	3.1±0.3	Low
45	0	4.3±0.2	Low
	3	5.5±0.4	Moderate
	5	6.4±0.4	Moderate
65	0	7.4±0.3	High
	3	9.1±0.9	Very high
	5	10.0±0.9	Very high

Figure 9. PSI (mean±SE) applied using T_{re} (left panel) and T_{es} (right panel) in evaluating the 9 experimental exposures. * Drop due to subject attrition.



The $\dot{m}_{sw}$, at 20 min of exercise, and the comparative PSI values are presented in Figs. 10 and 11. The $\dot{m}_{sw}$ and PSI values at the three exercise intensities and across the three hydration levels are presented in Fig. 10. Fig. 10 shows that $\dot{m}_{sw}$ increased with exercise intensity, and correlated well (r=0.99) with PSI. The $\dot{m}_{sw}$ at the three different hydration levels, across all exercise intensities, is presented along with the evaluation of the strain by PSI in Fig. 11. An inverse correlation is depicted between PSI and $\dot{m}_{sw}$ (r=-0.99). At higher hypohydration levels, the $\dot{m}_{sw}$ decreased while PSI values increased.

Figure 10. PSI (•) and sweat rate ($\dot{m}_{sw}$) (Δ) (mean±SE) after 20 min of exercise across the 3 hydration levels at the 3 exercise intensities.

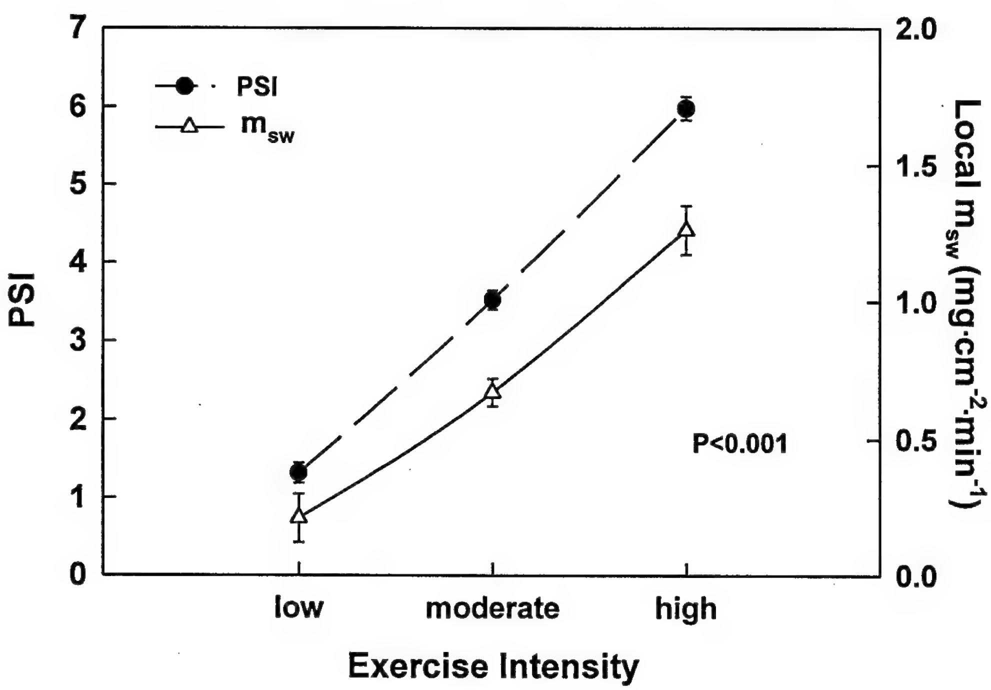
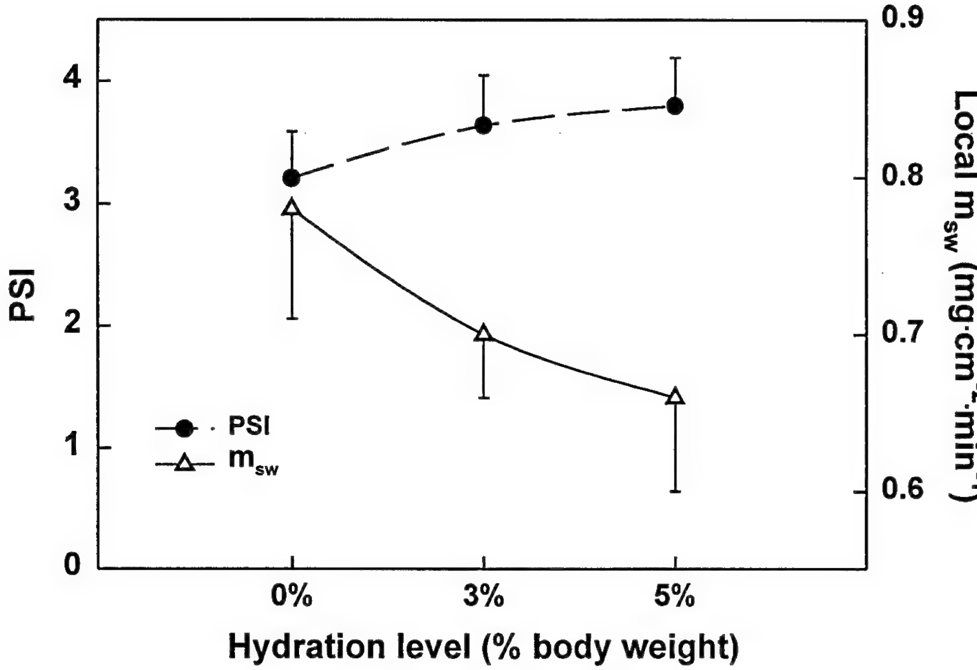


Figure 11. PSI (•) and $\dot{m}_{sw}$ (Δ) (mean±SE) after 20 min of exercise across the 3 exercise intensities at the 3 levels of hydration.



STUDY III

The purpose of this study was to examine the ability of PSI as a tool to evaluate and assess gender heat strain differences at various exercise intensities and climatic conditions. In addition, we aimed to evaluate the interactions between PSI and $\dot{m}_{sw}$ or relative exercise intensity from these same experiments.

No significant differences (P>0.05) were observed between M and W for age, weight, height, body mass index, and $\dot{V}O_{2max}$ (Table 1). However, $\dot{V}O_{2max}$ was significantly higher (P<0.05) for MF than M or W while age, weight, height, and body mass index did not differ between any of the groups. Therefore, the relative exercise intensity (%$\dot{V}O_{2max}$) during these experiments was the same for M and W but significantly lower for MF. This experimental design allowed us to test the ability of PSI

to discriminate apparent gender differences (MF vs. W), or when no differences should be found (M vs. W).

Generally, T_{re} elevated in the three groups (W, M and MF) in proportion to the magnitude of the exercise intensity, and increased progressively during exercise (Fig. 12). Significantly higher T_{re} values were observed in the hot climates (hot-dry and hot-wet) than for exposure to the comfortable climate ($P<0.05$). T_{re} dynamics, depicted as hyperthermic plateaus, were observed in the comfortable climate at each of the three exercise intensities. A very modest T_{re} increase was measured under the hot climates (hot-dry and hot-wet) during the low exercise intensity, whereas a continuous T_{re} increase was observed during the moderate and high intensities. The women's T_{re} during exercise was significantly higher when compared to values for M and MF groups ($P<0.05$). Furthermore, the women's initial T_{re} values were also the highest of the three groups in eight of the nine experimental exposures ($P<0.05$). Therefore, the overall T_{re} changes during exercise between the three groups at the same matched exposures were not significant. Higher values of T_{re} were measured in M than MF in all exposures. However, significant differences were found only in the hot-wet climate at moderate and high exercise intensities ($P<0.05$).

When compared to T_{re}, similar HR dynamics were observed (Fig. 13). However, HR reached a plateau for the three groups in six out of the nine total exposures, including all exposures at the low exercise intensity and all exposures during the comfortable climate. Highest absolute HR values were observed for W. However, no significant differences were found between W and M, whereas, significant ($P<0.05$) HR differences were found between W and MF at all exercise intensities under hot-dry and hot-wet climates, and at the high exercise intensity for the comfortable climate. Significantly higher ($P<0.05$) HR values were measured for M when compared to MF. However, these differences were not significant during the low exercise intensity at the three climates and during the moderate exercise intensity at the comfortable climate.

T_{sk} was significantly lower during the comfortable climate than in hot climates ($P<0.0001$). T_{sk} values were significantly lower in MF than in W ($P<0.005$), but no differences were found between W and M.

Figure 12. T_{re} dynamics (mean±SE) of 3 groups (women, men, and men-fit) who participated in 9 experimental exposures consisting of 3 exercise intensities (low, moderate, and high) and 3 climates (comfortable, hot-wet, and hot-dry). Data from men-fit at the low exercise intensity during comfortable climate are not available.

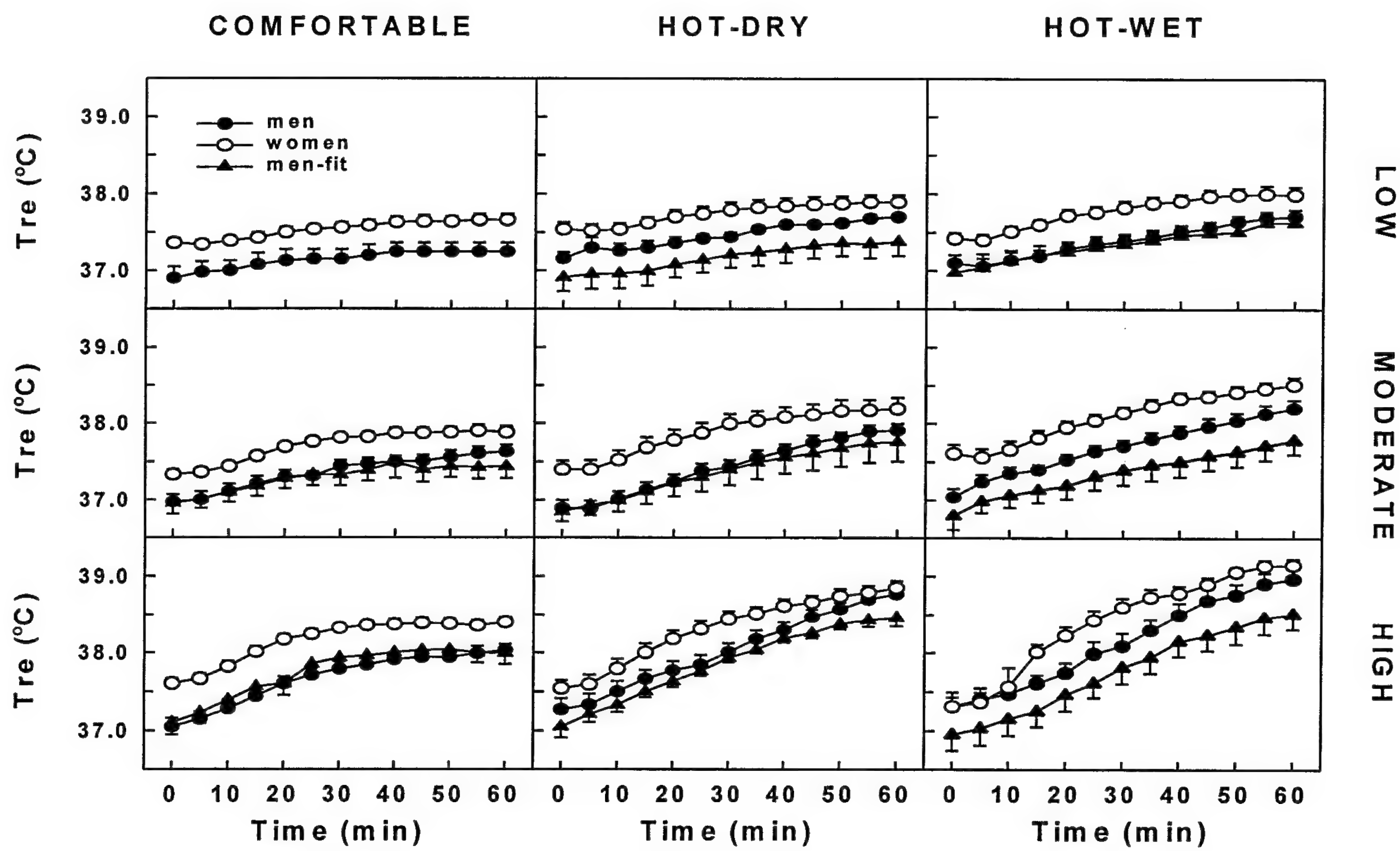
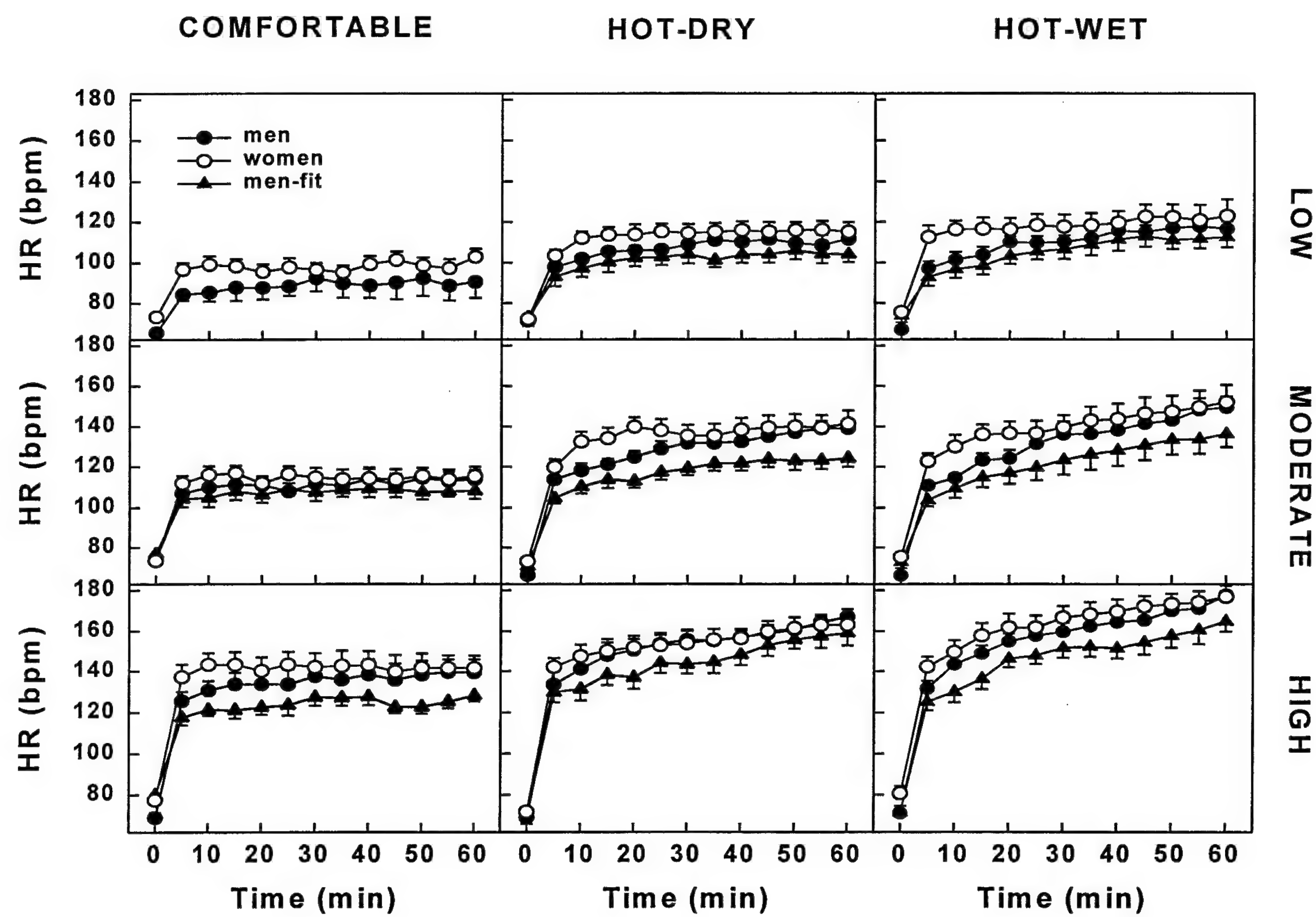


Figure 13. HR dynamics (mean±SE) of the 3 groups who participated in these 9 experimental exposures.



Generally, PSI values progressively increased with exercise intensity and environmental heat load (Fig. 14). Significantly lower values ($P<0.05$) for PSI were observed between the comfortable climate than either the hot-dry or hot-wet climates; however, differences between climates were not significant at the low exercise intensity. Higher absolute PSI values [not significant ($P>0.05$)] were observed for the hot-wet than for the hot-dry climate. The PSI evaluated the W group with the highest values, but significant differences ($P<0.05$) were found only between W and MF at the high exercise intensity for the three climatic conditions, and at the moderate exercise intensity for the two hot climates. No significant differences for PSI were found for the matched exposures between W and M groups. Higher absolute PSI values were found in M than MF for all exposures. However, significant differences between M and MF ($P<0.05$) were as follows: (a) moderate exercise intensity for 60 min at the hot-wet climate, and from 45 min to the end of the exposure at the hot-dry climate; (b) high exercise intensity from 45 min to the end of the comfortable climate, from 35 min at the hot-wet climate, and the last 10 min of the hot-dry exposure.

The PSI rated the strain in rank order according to the combined exercise intensity and the climate condition. Applying PSI, from the beginning to the end of exercise, across the three climate conditions revealed that the low exercise intensity was ranked as little to low strain with values of 2-4, while the moderate exercise intensity was ranked as little to moderate strain with values of 2-6. The high exercise intensity was ranked from low to very high strain with values of 2-9.

Sweat rate ($\dot{m}_{sw}$) and the calculated PSI for the subjects for the different exposures are shown in Fig. 15. In general, $\dot{m}_{sw}$ correlated with exercise intensity and environmental heat load. The higher the work load, the higher the observed $\dot{m}_{sw}$. In addition for the hot climates, $\dot{m}_{sw}$ was about twice that during the comfortable climate for the same exercise intensity. The highest $\dot{m}_{sw}$ values were measured for the MF while significantly different ($P<0.05$) values were found between MF and W at the high exercise intensity in the two hot climates. No significant differences were found between M and W for $\dot{m}_{sw}$. As depicted in Fig. 15, there is a high correlation (r=0.97) between $\dot{m}_{sw}$ and PSI for the same climatic condition at the different exercise intensities. However, there is an inverse correlation (r=-0.95) between $\dot{m}_{sw}$ and PSI when analyzed for the different groups at the same exposure (climate and exercise intensity). Thus, higher $\dot{m}_{sw}$ is reflected as lower physiological strain when compared among these three groups.

Figure 14. PSI (mean±SE) applied using T_{re} (Fig. 12) and HR (Fig. 13) in evaluating these 9 experimental exposures.

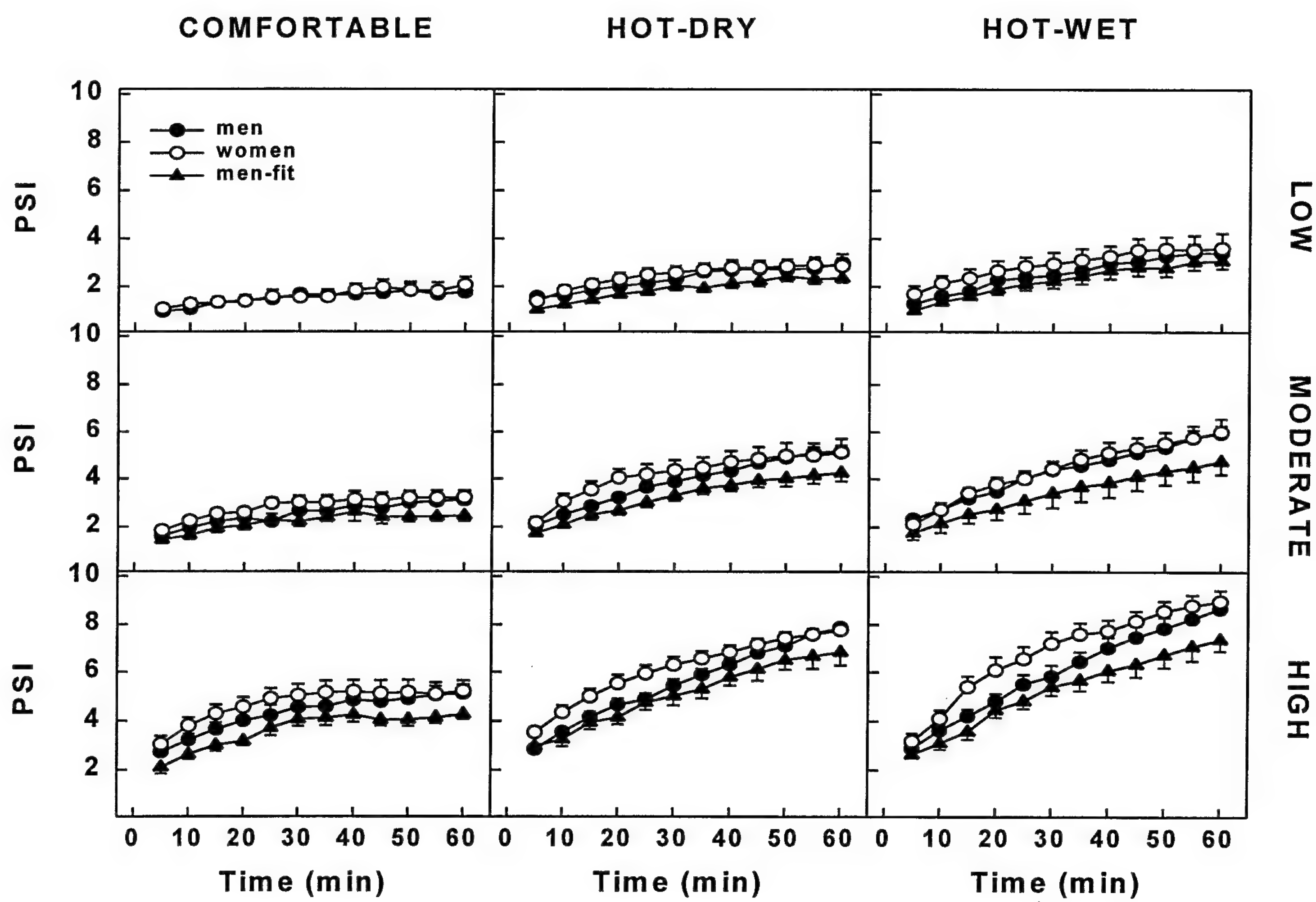


Figure 15. PSI and $\dot{m}_{sw}$ (mean±SE) after 60 min for the 3 groups in these 9 experimental exposures.

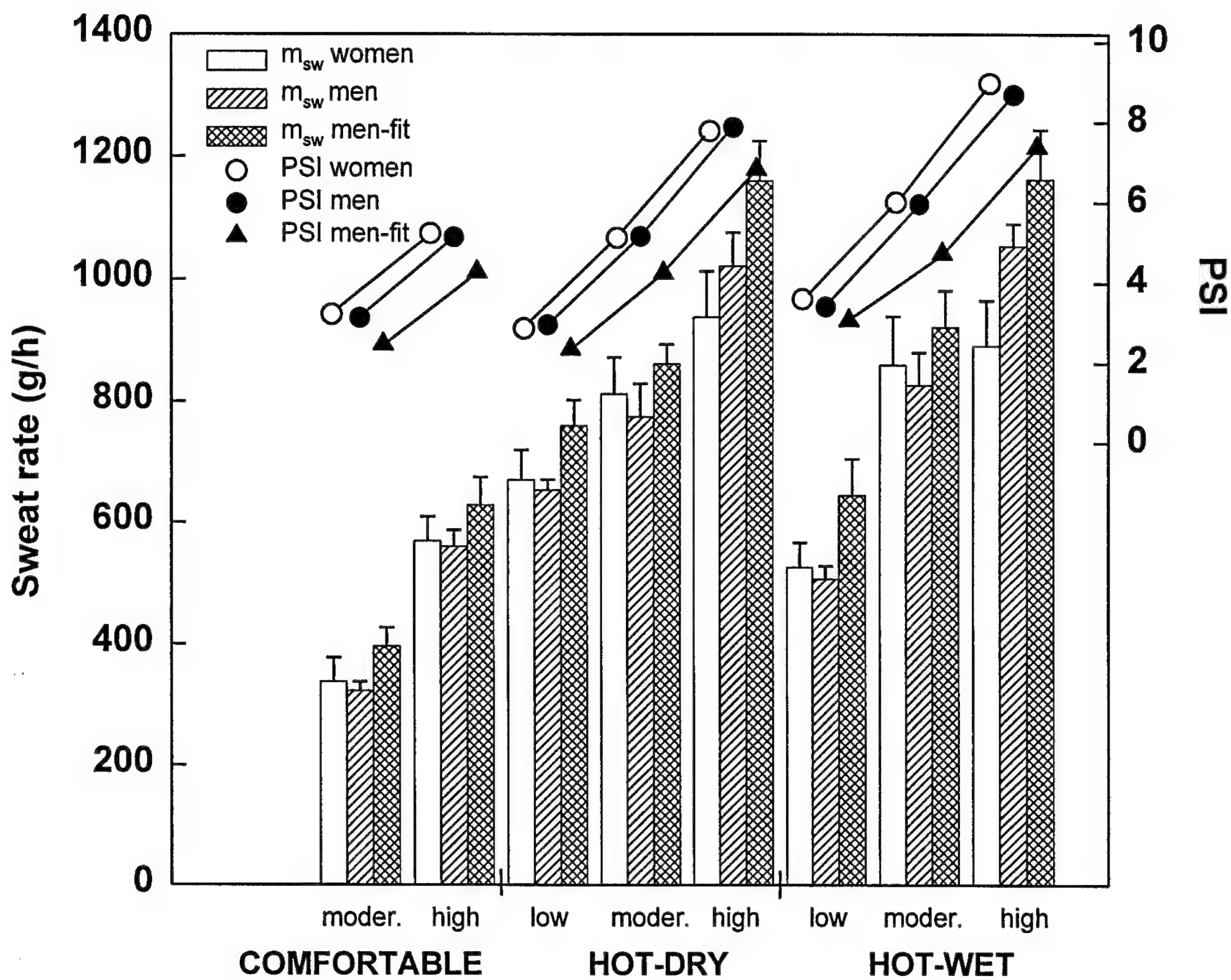
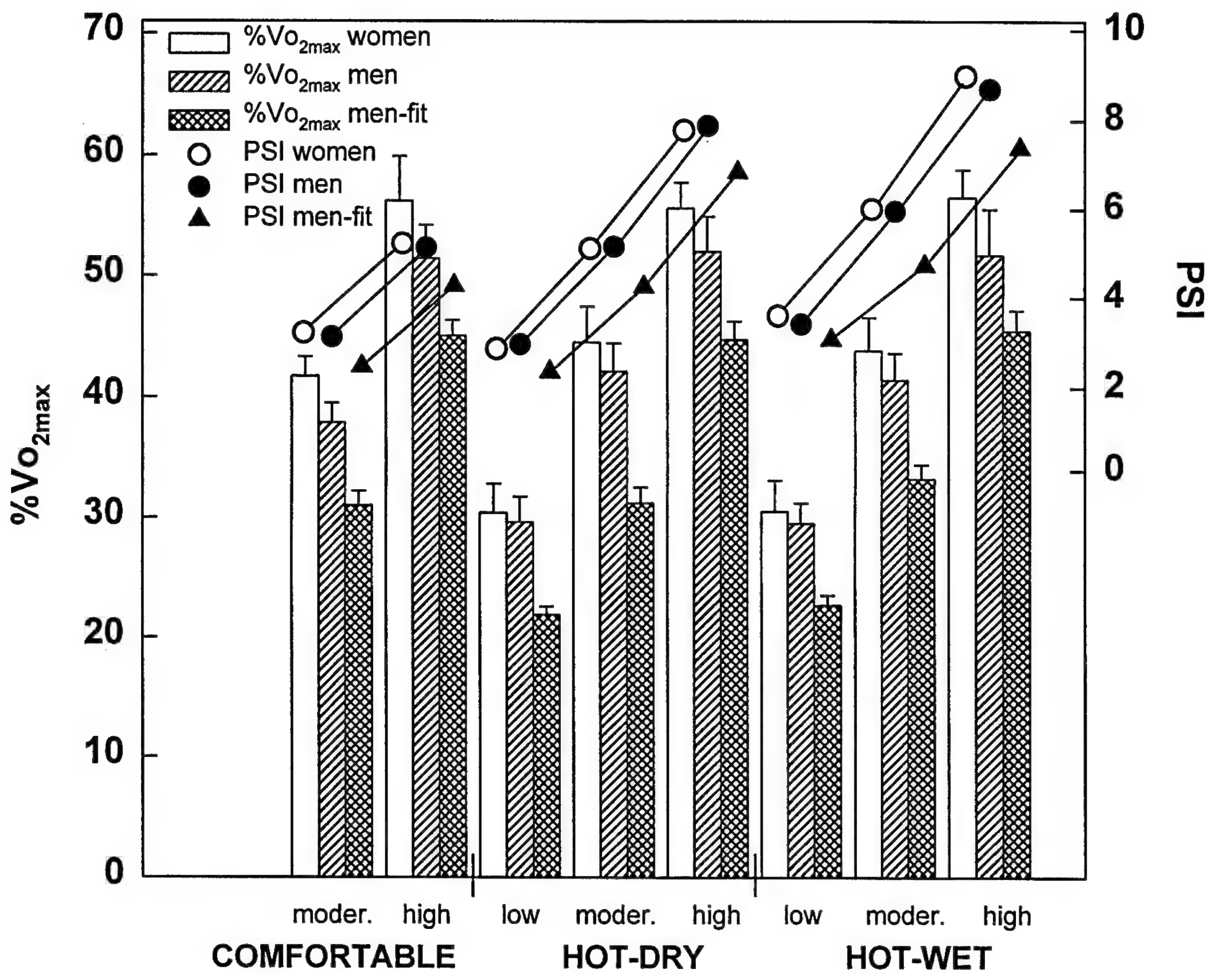


Figure 16. PSI and $\%\dot{V}O_{2max}$ ($\dot{V}O_2/(\dot{V}O_{2max})$ (mean±SE) after 60 min for the 3 groups in these 9 experimental exposures.



The relative oxygen consumption (%$\dot{V}O_{2max}$) and the simultaneously calculated PSI are depicted in Fig. 16. Generally, significant differences (P<0.01) were found in %$\dot{V}O_{2max}$ between the different exercise intensities. However, no significant differences were found between the same exercise intensities for the different climatic conditions. In all experimental exposures, the lowest %$\dot{V}O_{2max}$ values were calculated for MF and found to be significantly (P<0.05) different from W or M. However, no significant differences were found in %$\dot{V}O_{2max}$ between W and M. High correlations were found between %$\dot{V}O_{2max}$ and PSI in two different statistical analyses. First, for the different exercise intensities under the same climatic conditions (r=0.99), and second, when compared between the different groups for the same exercise intensity and climatic condition (r=0.96).

DISCUSSION

STUDY I

The present index to evaluate heat strain describes well the physiological strain on a universal scale of 0-10. This index is based on only two physiological parameters: HR and T_{re}, which adequately depict the combined strain reflected by the cardiovascular and thermoregulatory systems. Both systems are assumed to contribute equally to the strain by assigning the same weight function to either one. However, this simply constructed index, enables separate analysis of each one of the two systems contributing to the strain (Eq. 3).

PSI differs from other indices that have been suggested in the past. The CHSI (11), which was also based on T_{re} and HR, was found to be a valid model in estimating heat tolerance, but it is limited in its use for three major reasons. First, the index could only compare subjects exposed for the same duration. The values predicted by this index were very large (~0-4000), and completely different values could be obtained at varying durations, which did not necessarily relate directly to the strain (11). In addition, the CHSI (a multiplication of HR and T_{re}) depicted a hyperbolic curve pattern, with almost no strain during the first hour of exercise (Figs. 1, 4). The hyperbola is a contradiction to the dynamics of the physiological parameters (HR and T_{re}) and might be misleading in analyzing the strain when evaluating the index curve. Second, the CHSI continued to rise during a steady state or recovery period, although T_{re} and HR decreased (Fig. 1). As a consequence, the validity of CHSI has been limited to exposures with no rest or recovery periods. Furthermore, this index, which is based from on-line measurements and calculations, would be limited to on-line use only. Third, CHSI was based on heart beats rather than on HR. This posed some difficulties in using the index, as it is not common to measure heart beats. The implications of CHSI with HR at different time intervals could affect its accuracy.

These limitations categorized the CHSI like most heat strain indices, as an index that applied to a particular type of exposure. However, when we compared the strain between hot/dry and hot/wet in a study by Montain et al. (39), the CHSI and the PSI succeeded in rating the hot/dry climate conditions with a higher strain; unlike HSI, which rated the hot/wet with a higher strain (Fig. 4).

The HSI uses the approach that the ratio of E_{req}/E_{max} provides a meaningful index, but was presently found to be limited (3). This index was based on many components, calculations, and involved more than fifteen variables (e.g., ambient temperature, barometric pressure, wind velocity, ambient water vapor pressure, skin temperature, skin water vapor pressure, clothing insulation coefficient, water vapor permeability of clothing coefficient, body surface area, metabolic rate, external work load, heat exchange by radiation and convection) which made it inconvenient to use, and also could be a source for errors. There were conditions in which HSI was limited in its ability to rate heat stress, i.e., while wearing light clothing which causes E_{req} = E_{max} , or while wearing protective garments which create a microclimate different from the environment (25, 30). These limitations necessitated the development of additional criteria, restrictions, and corrections for improving the prediction of HSI. It can be concluded from the Montain et al. study (39) that HSI failed to rate the exposures in hot/dry climate conditions with higher strain, because subjects were dressed in protective clothing (Fig. 4).

Among the possible criteria to construct a new PSI, we considered T_{re}, HR, $\dot{m}_{sw}$ and T_{sk}. It was deemed essential to include T_{re} and HR. T_{re} reflects the body heat storage, and is elevated during exercise because of the partial accumulation of heat produced as a by-product of skeletal muscle contraction. HR reflects the demands of the circulatory system. It is an immediate effector of the vasomotor response to metabolic and environmental conditions (38).

After McArdle et al. (33) developed the P4SR index to describe heat strain, it was debatable whether $\dot{m}_{sw}$ by itself could be a valid measure of strain. Hatch (22) and Belding (3) argued that $\dot{m}_{sw}$ does not only reflect the physiological heat strain, but it can also be affected by dehydration. We believed that $\dot{m}_{sw}$ was a valid criteria when combined with HR and T_{re}. However, since we decided to develop an on-line index, $\dot{m}_{sw}$ was not included because of the difficulty to measure it on-line. T_{sk} is also a well-known criterion of heat strain. While T_{sk} is higher in warm environments, T_{re} is relatively unaffected by ambient temperature over a wide range (58). As a response to higher T_{sk}, skin blood flow increases to achieve core-to-skin heat transfer for thermal equilibrium. Elevated T_{sk} is associated with reduced cardiac filling and stroke volume, therefore, the way to maintain cardiac output is by increasing HR (58). Thus, we concluded that physiological strain could be adequately represented by the stress factors of HR and T_{re} only.

Our first attempt was to develop a new integral stress index (ISI). This index assumed that the maximum values of HR and T_{re} during heat stress were 180 bpm

and 39.5°C, respectively (Eq. 4). It rated the stress on a scale of 0~15 in the same curve pattern as HR and T_{re} were depicted. However, during the recovery or rest period, ISI continued to rise, producing limitations in its applicability.

The new PSI is designed for both the layman and the scientist. This index is simple to use, scaled to a range of 0-10, where 0 represents no strain and 10 represents very strenuous physiological conditions. It is based from on-line calculations at different time intervals. Thus, unlike the HSI and other models, PSI is computed while the subject is exposed to stress with no need to wait until the end of the exposure in order to analyze the strain. Since it is calculated by HR and T_{re} measurements, it can be applied at any time, including rest or recovery periods, whenever these parameters are measured. This characteristic can not be achieved by any other existing heat strain index. Furthermore, unlike most heat strain indices which involve many variables and parameters, PSI calculations involve only two parameters, which helps decrease the source of error. Moreover, the principle behind PSI is evaluation of the physiological strain resulting from the cardiovascular and the thermoregulatory systems. Therefore, the strength of this index is its ability to rate and compare the strain between any combination of climate and clothing. It is believed that the PSI suggested in this study is unique, in that it yields a quantitatively descriptive figure of heat strain at any time point.

It is well known that the physiological heat strain for middle-aged men and women during physical work in the heat is greater than that observed for younger individuals (47). The greater physiological strain is indicated mainly by higher T_{re} and HR values. Due to the fact that the subjects participating in the present study were young men, we assumed that 3°C and 120 bpm were the maximal rise (for T_{re} and HR, respectively) from normothermia to hyperthermia during exposure to heat stress. However, several investigators showed that tolerance to heat stress for the general population of middle-aged men and women is less than for those younger (47). In order to apply PSI to women and different age groups, more studies should be done for proper validation.

STUDY II

The PSI, for the two different databases under investigation, accurately described the heat strain of men dehydrated to four different levels during 120 min of cycling, and the strain accompanying a matrix of three exercise intensities and three hypohydration levels. Our index succeeded in rating each one of these exposures on its universal scale of 0-10. The index, which is based on only two physiological parameters: HR and core temperature (T_{re} or T_{es} in this study), categorized every exposure in the proper and expected order; whereas HR, T_{re} and T_{es} during the different exposures were limited in their individual ability to categorize each exercise intensity - hypohydration level combination separately (Figs. 5, 7, 8).

During the last century, more then 20 heat strain indices have been proposed (3, 31). However, not one has been accepted as a universally valid index for rating heat stress. This is mainly attributed to the number and complexity of the interactions among the determining factors (3, 43). The ability to sustain exercise in the heat depends mainly on the effective heat transfer from the contracting muscles to the skin, and from the skin to the environment. Dehydration compromises blood flow to the skin, resulting in greater thermal and cardiovascular strain. Thus, when hypohydration accompanies heat-stress, it causes even more difficulties in evaluating the resultant physiological strain. The combination of many different levels of hypohydration and different exercise intensities provided by our two unique databases challenged the ability of PSI to discriminate the relative strain of exercise in the heat.

It is well known that T_{es} values are generally lower than simultaneous T_{re} measurements (45, 54). T_{es} responds rapidly and quantitatively to changes in blood temperature with a time constant of ~1 min, whereas T_{re} responds more slowly with a time constant of ~12 min (e.g., during exercise) (58). To further the appreciation of the versatility of the PSI, we examined the physiological strain using both T_{re} (PSI_{Tre}) and T_{es} (PSI_{Tes}) measurements.

The simultaneous measurement of T_{re} and T_{es} in both database sets revealed higher T_{re} ($P<0.01$) (Figs. 6, 8). Therefore, it was expected that PSI_{Tre} would result in higher values than PSI_{Tes}. This was true for the first database, as PSI_{Tre} was significantly higher than PSI_{Tes} by ~0.5-1.0 unit ($P<0.01$). However, in the second database, PSI_{Tre} was not significantly higher than PSI_{Tes} during exercise at 25% and 45% of $\dot{V}O_{2max}$. PSI_{Tre} was highest during the higher exercise intensity (65% of $\dot{V}O_{2max}$) (Fig. 8). These minor differences between PSI_{Tre} and PSI_{Tes} are attributed to the PSI construction which normalized each physiological parameter (HR and T_{re} or T_{es}) to its initial value. Regardless, it can be concluded that PSI_{Tes} and the original PSI (PSI_{Tre}) are both able to provide meaningful values for estimating different levels of hypohydration during exercise heat-stress, including severe conditions in which body heat balance was violated.

The two databases used supported earlier observations that hypohydration increases T_{re} and HR during exercise in the heat (56-58). Furthermore, as the severity of hypohydration increases during exercise in the heat, there is an associated increment in the elevation of T_{re} and HR. The incrementally increased T_{re} had been associated with a decreased $\dot{m}_{sw}$. Correspondingly, it was expected that T_{re} ,T_{es} and HR could be used for physiological strain assessment. T_{re} and T_{es} reflect the body heat storage, and are elevated during exercise proportional to exercise intensity. HR reflects the demands of the circulatory system. Unlike T_{re}, HR rapidly responds to changes in metabolic demands and environmental conditions (40). However, as depicted in Figs. 5, 7 and 8, T_{re}, T_{es} and HR were limited in their ability to individually quantify and to categorize the different experimental exposures. On the other hand, applying PSI to the same database containing T_{re} or T_{es} and HR measurements, clearly evaluated the relative strain with a simple scale ranging from 0-10 (Fig. 9). In

fact, PSI well described the physiological strain at the different exercise intensities and hypohydration levels, according to classic physiology: a) exercise intensity correlated with the physiological stress and with $\dot{m}_{sw}$ (Fig. 10), and b) hypohydration level correlated with the physiological stress and inversely correlated with $\dot{m}_{sw}$ (Fig. 11). The commonly use RPE scale was also correlated with hypohydration levels. However, although RPE correlated with PSI and discriminated between the different hydration levels, it was limited in significantly differentiating between two exposures (1.1% and 2.3% BWL), unlike the PSI.

PSI, unlike other heat strain indices, depicts the combined strain reflected by the cardiovascular and thermoregulatory systems. This enables PSI to compare between different studies. The first database, analyzed in this study, was collected for 120 min, whereas the second database was obtained for 50 min. However, a comparison of PSI between the two databases for similar exposures (65% $\dot{V}O_{2max}$ ~3% BWL) after 50 min of exercise revealed the same moderate strain category values of 6.0 and 6.4 (for the first and the second databases, respectively). In a previous study, PSI showed the ability to assess heat strain at different combinations of metabolic rate, climate condition, and clothing (42). In this study, we were able to extend its evaluation to different combinations of hypohydration levels and exercise intensities in the heat using either T_{re} or T_{es}, and RPE.

STUDY III

The PSI for the three groups (W, M, and MF) under investigation correctly described the relative heat strain while these subjects were exposed for 60 min to a matrix of three exercise intensities (300W, 500W, 650W) and three different climate conditions (20°C, 50%RH; 40°C, 35%RH; 35°C, 70%RH). The PSI rated each one of these exposures on a universal scale of 0-10. In spite of the variability in HR and T_{re}, the PSI, which is constructed from these two parameters successfully, categorized the physiological strain for the three experimental groups in the expected order. The focus of this paper was to determine the ability of PSI to discriminate between W, M, or MF during these exposures; and, to study the relationships between PSI and $\dot{m}_{sw}$ or relative exercise intensity as a function of $\dot{V}O_{2max}$ for gender during these same experiments.

T_{re} values during all nine experimental exposures for the W group were markedly higher than for M and MF. Since we did not control for menstrual cycle phase in these experiments, our findings cannot be directly related to the reported impact of menstrual cycle phase (26, 36, 60). Other investigators showed about a 0.4°C higher core body temperature in the luteal phase than the follicular phase (53). However, in spite of the higher T_{re} values observed during the W exposures, PSI successfully categorized the W heat strain. The latter is attributed to the PSI construction, which normalizes each physiological parameter (T_{re} and HR) for its initial value. In view of the fact that this procedure alters the span of the index, PSI was constructed in order to be scaled to a simple range of 0-10 without affecting its

predictive accuracy as shown in this and other papers (41, 43). Thus, although Figs. 12-13 depict higher T_{re} and HR values for women, the PSI indicated the relative changes in the actual heat strain of the three groups and correctly discriminated between the nine exposures consisting of three exercise intensities and three different climates (Fig. 14).

The $\dot{m}_{sw}$ correlated highly with exercise intensity and also with PSI. These findings are in accordance with earlier observations found between local $\dot{m}_{sw}$ and PSI (41). However, analysis of our three groups at the same workload revealed an inverse correlation between $\dot{m}_{sw}$ and PSI as depicted in Fig. 15. The $\dot{m}_{sw}$ for the W was not different from the M, which agreed with the non-significant differences in aerobic fitness between these two groups. Some investigators have claimed that women are more efficient sweaters than men in a hot-wet climate (2, 12). In our study, there were no significant gender differences in $\dot{m}_{sw}$ for the hot-wet and hot-dry climates.

In study I, PSI assessed higher strain under a hot-dry than hot-wet climate. However, in this study our hot-wet climate assessed the higher strain. The best explanation for the contradiction in these assessments is probably the subjects' different clothing. In study I, subjects exercised wearing protective garments, while in this study subjects dressed only in shorts (women with bras as well). Protective garments create a microclimate different from the environment which does not necessarily reflect the same environmental stress while wearing only shorts or standard cotton clothing (25, 29). Moreover, the principle behind PSI is the evaluation of the physiological strain resulting from the cardiovascular and the thermoregulatory systems. Therefore, various combinations of climate and clothing can result in different PSI assessments. The strength of this index is its ability to quantitatively rate and compare the strain between different exposures at any time point.

In our study, matching between genders (M and W) was mainly done according to $\dot{V}O_{2max}$. In addition, all three groups (M, W, MF) did not differ (P>0.05) for age, height, weight and body mass index (Table 1). However, %$\dot{V}O_{2max}$ values during all of the different exposures were still slightly higher for W than for M (Fig. 16). The only significant physiological parameter that was different between these groups (MF vs. M or W) was $\dot{V}O_{2max}$, and PSI accounted for these differences between genders when evaluated as a % of $\dot{V}O_{2max}$. Therefore, the aerobic fitness of these individuals was the most important variable for matching genders when exposed to exercise-heat stress. These findings also support those of previous investigations (2, 12), which reported that when men and women were matched for $\dot{V}O_{2max}$ and select physical characteristics, their physiological performance post acclimation was essentially the same in both hot-dry and hot-wet environments.

SUMMARY

Although there are many heat strain indices, we found that they were valid only under certain and specific conditions. The present study suggests a simple valid physiological strain index to evaluate heat stress either on-line or when data analysis is applied. This index should be easier to interpret and use than other indices available, and includes the ability to depict rest and recovery periods. PSI is capable of overcoming the limits of previous indices, while providing the potential to be widely accepted and used universally. However, further investigation is required to possibly adjust this index for different age groups. The PSI successfully evaluated the heat stress in subjects who exercised in a warm environment at different exercise intensities combined with different levels of hypohydration. This index overcame the individual limits of the physiological parameters (T_{re}, T_{es} and HR) in assessing heat stress for this study, and continues to provide the potential to be accepted universally. The PSI also successfully evaluated heat stress in genders who exercised at different intensities in different climates. We have also extended the applicability of PSI in the present study to consider sweat rate and relative exercise intensity as a function of climate. Therefore, PSI applicability was further extended for exercised-heat stress and gender at different combinations of exercise intensity and climate, and continues to show potential to be widely accepted.

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